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Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
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NOTICE

Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

Persons who are not members of the Society of Economic Paleontologists and Mineralogists or are not subscribers to the *Journal of Sedimentary Petrology* but who desire to publish an article in the *Journal,* should have some member of the Society of Economic Paleontologists and Mineralogists or some member of the American Association of Petroleum Geologists sponsor the article. Members of these Societies are given preference in publication.

Among papers to appear in forthcoming issues of the *Journal* are the following:

Aragonite tests among the Foraminifera. By Orville L. Bandy.

Stylolite development post-dates rock induration. By H. V. Dunnington.

Some characteristics of Southern California sediments. By K. O. Emery.

Photomicro-stereographs as an aid in interpreting textures and structures. By R. J. Hughes, Jr.

The energy factor in sedimentation. By W. D. Keller.

The tetrahedron as a facies mapping device. By W. C. Krumbein.

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FIGS. 1–6, PLATE 1, DECEMBER, 1953

PETROLOGY AND SEDIMENTATION OF UPPER CHESTER SANDSTONES[1]

RAYMOND SIEVER
Illinois Geological Survey, Urbana, Illinois

ABSTRACT

A study of the mineral constituents and textures of upper Chester sandstones in Illinois was undertaken to throw light on environments of deposition, tectonic activity, and possible source areas. Although there are many minor facies changes in all the sandstone beds, all except the Menard and Kinkaid sandstones are persistent over wide areas in the Eastern Interior Basin. Most of the sandstone beds are dominantly quartzose, with minor admixtures of clay minerals, carbonate, rock fragments, and accessory minerals. Most of the sandstones are well-sorted clean orthoquartzites, but many sandstones have a composition more like that of a subgreywacke. Many of the sands show evidence of having been winnowed and reworked at the site of deposition. The sedimentary environment is reconstructed from petrographic and stratigraphic data as dominantly sublittoral, near-shore, with brackish or marine waters, although there is evidence that some of the sands were deposited on a terrestrial coastal plain. The mineral composition of the sands, considered in conjunction with the amounts of coarse clastic material in other areas of deposition during Chester time, points to northern sources of detritus rather than sources to the east.

This investigation is concerned with the sandstones of the upper half of the Chester series (Upper Mississippian) in the Eastern Interior Basin. This basin, which persisted through much of the Paleozoic era, covers much of Illinois and adjacent parts of Indiana and Kentucky. In this area Chester stratigraphy has been worked out in great detail, both from outcrop and subsurface studies (Weller & Sutton, 1940; Workman, 1940).

The purpose of this study is threefold: (1) to determine petrographically the provenance, or source, of the detritus which makes up the clastic portion of these rocks; (2) to determine the general characteristics of the sedimentary and tectonic environment in which the rocks were formed; and (3) to relate the sedimentary petrography of the rocks to the details of sedimentary structure and stratigraphy. This paper presents the first results of a long-range study of the petrography and origin of the clastic Paleozoic sediments in the Eastern Interior Basin.

[1] Published by permission of the Chief, Illinois Geological Survey.

STRATIGRAPHY

The general character of the Chester succession in the Eastern Interior Basin is that of a thick transition zone of mixed carbonate and clastic rocks lying above the dominantly carbonate rocks of the Lower Mississippian and below the dominantly clastic rocks of the Pennsylvanian. Stuart Weller (1920) was the first to divide the Chester series into 16 alternating sandstone and limestone-shale formations and to point to the cyclical character of the sediments (fig. 1). Cyclicity is suggested not only by repeated lithologic alternations but by unconformities at the bases of the sandstones, which have been thought to be largely nonmarine. Thus each limestone-shale formation may be paired with an underlying sandstone formation, each pair separated by an unconformity. Thin coal beds at the top of some of the sandstones increase the resemblance to the cyclical units in the Illinois Pennsylvanian, which J. M. Weller (1930) has described.

The abundant subsurface information which has become available in recent years has shown that, although the cycle

concept still holds as a generalization, qualifications must be added that complicate the picture. In some areas the mixture of shale, sandstone, and limestone in the various formations is distributed vertically in such a way that any generalization as to repetitive order of beds is impossible. A study of the subsurface sections shows that shales are associated not only with limestone beds but just as abundantly with sandstone beds. Further, there are several relatively persistent sandstones associated with limestone beds.

One interpretation of the cyclical sequence is that there was a constant influx of shaly material intermittently diluted with quartz sand. During periods when quartz sand was supplied from the source area, more or less argillaceous sands were deposited. During periods of greater stability, when there was little available quartz sand, shales and limestones were deposited. There may have been no great difference between the sedimentary environmental conditions for these different types of deposits; rather there was a difference in the degree of tectonism of the source area and therefore of the kind of detritus supplied.

Extreme lateral variation in lithology and thickness of sandstone and shale beds is a striking feature of the Chester series, just as it is of the overlying Pennsylvanian (fig. 2). Sandstones may grade laterally into shale within a distance of a mile or less. This is the dominant type of local stratigraphic variation. In general, the limestone beds are more uniform in thickness over wide areas. Superimposed on this local variation are regional facies changes, such as Swann (1948) has discussed, involving thickness and lithology of beds and the numbers and kinds of members of the formations. Swann (1951) made a valuable delineation of the lateral variation of one Chester sandstone, the Waltersburg. His maps show that Waltersburg sand bodies are definitely linear and are uniformly oriented northeast-southwest. The significance of the shapes of these sand bodies is discussed below.

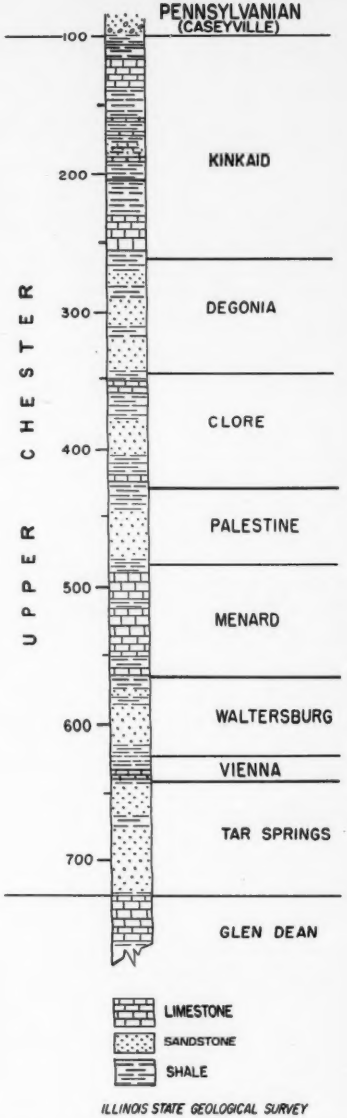

FIG. 1.—Generalized section of upper Chester formations in Illinois (after Siever, 1951).

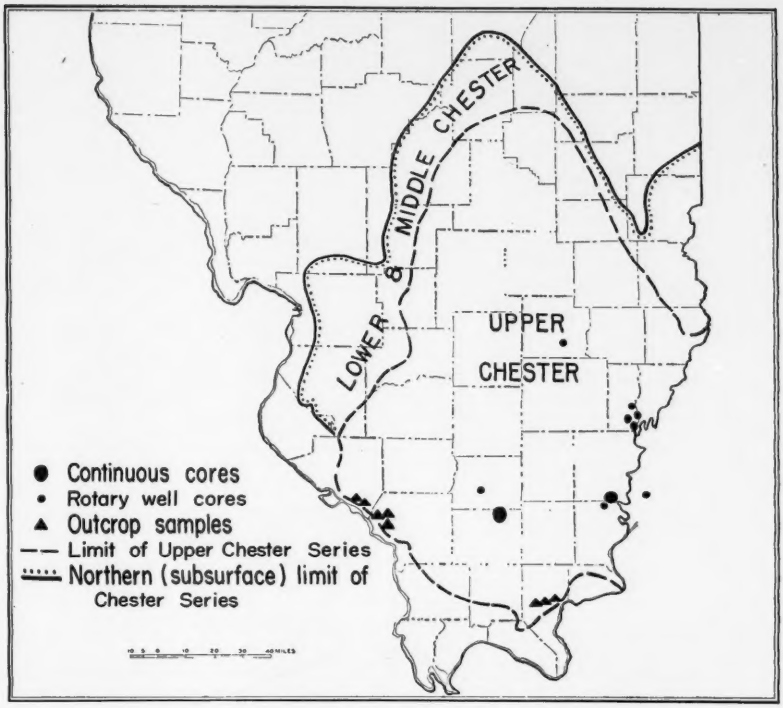

FIG. 3.—Distribution of upper Chester sandstone samples (Indiana samples not shown).

SEDIMENTARY PETROGRAPHY

Some of the samples chosen from upper Chester formations come from outcrops in southwestern Illinois near the type areas of many Chester formations. Some were collected in southeastern Illinois and in Perry County, Indiana. The other samples come from two continuous diamond drill cores taken in White and Williamson counties, Illinois, and scattered cores from rotary drill holes in various parts of the Illinois Basin (fig. 3). Mineral composition, estimates of size distributions, and roundness of grains were determined from study of thin-sections. Clay minerals were identified tentatively by optical means and checked by differential thermal analysis and X-ray diffraction.

The sandstones of the upper Chester series are variously bedded, from thinly laminated to massive. Bedding is a function of grain size variation and mineral composition, most commonly the mixing of varying amounts of clay minerals with quartz sand particles. Although many sandstone and siltstone beds are thinly laminated, rock sequences do not show graded bedding. Cross-bedding of several types is commonly present and ripple marks are prominent on many surfaces. Slump structures, such as contorted and convoluted bedding, and small slips or "micro-faults" are present but not common.

The detrital quartz fragments range

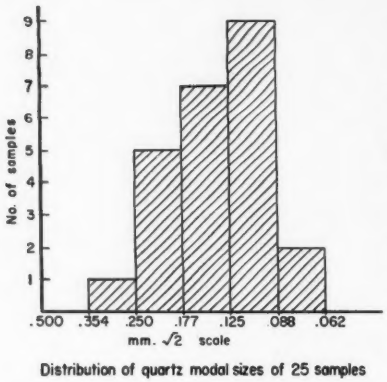

FIG. 4.—Distribution of modal sizes of upper Chester samples.

from fine silt to coarse sand in size. However, the dominant fraction of the grains falls into the finer grades of sand. Only three of the measured samples showed any grains of coarse size, greater than 0.5 mm. The modal sizes, with few exceptions, fall into the fine and very fine sand grades, averaging 0.14 mm. The distribution of the modal sizes of 25 samples is shown in figure 4. For the most part the size ranges indicate well-sorted sands. About 80 percent of the sand in most of the samples covers a range of only 4 or 5 ϕ grades. There is little variation of size distribution with stratigraphic position in upper Chester strata; rather the variation of size distribution is linked with mineralogy and texture. For example, the very calcareous sandstones are typically coarser-grained than the very argillaceous sandstones.

The roundness of the original detrital grains, not to be confused with apparent roundness of grains which have been secondarily enlarged, shows slight variation. The roundness, estimated by the visual roundness chart of Krumbein (1941), is in the range from 0.4 to 0.6 with a few samples showing averages up to 0.7. Thus, almost all the grains are rounded or well-rounded according to the classification proposed by Pettijohn (1949, p. 51). No attempt was made to measure sphericity of grains.

The mineral composition of these sandstones is one of the most important keys to their origin. Table 1 summarizes the mineral composition of 25 samples. Quartz ranges from 63 to 97 per cent. Clay minerals vary from a trace to 30 per cent. Carbonate minerals vary from a trace to 34 per cent. Many other minerals are found in small amounts. Argillaceous rock fragments are present in almost all the samples in small amounts. Chert fragments average about 2 to 3 per cent, although they make up as much as 10 per cent of some samples. Feldspar is present in almost all the samples but rarely exceeds 1 per cent, and the highest abundance measured was 5 per cent.

Several varieties of detrital quartz have been distinguished in the thin-sections. The most abundant variety is strain-free quartz, with planes of liquid and gas inclusions, which is of ultimate igneous derivation. Quartz of metamorphic origin, either showing extreme strain shadows or consisting of a mosaic of many small intergrown crystals, does not exceed 10 per cent of the total quartz except in the samples coming from the Indiana outcrop section, where these varieties constitute as much as 25 per cent of the total quartz.

Another variety of quartz found in almost all the sections is sedimentary or reworked quartz grains. These grains show a primary detrital grain which has been rounded, secondarily enlarged, and then rounded again, indicating erosion from a preexisting sediment in which secondary enlargement took place. It is difficult to assess the significance of the various igneous and metamorphic quartz varieties in terms of their immediate derivation from an igneous, metamorphic, or sedimentary terrain. Probably many of the igneous and metamorphic grains are actually second-cycle grains, but they do not have dusty boundaries which would indicate rounded secondary overgrowths and identify them as such.

The small amount of feldspar in these

TABLE 1.—*Petrographic analyses of 25 upper Chester sandstones (in per cent by volume)*

Sample No.	Stratigraphic position	Quartz	Clay	Carbonate	Chert	Feldspar	Quartz size		Roundness
							Mode	Range	
54	Kinkaid	71	20	4	3	tr.	.10	.04–.22	.6
51	Degonia	89	6	0	2	tr.	.10	.02–.18	.4
52	Degonia	70	10	0	10	5	.15	.02–.30	.5
53	Degonia (lower)	92	5	0	2	tr.	.14	.03–.28	.5
4-284	Degonia (upper)	79	8	7	2	2	.10	.05–.23	.5
30	Degonia (upper)	82	7	4	4	tr.	.25	.06–.50	.5
31	Degonia (middle)	88	6	1	2	tr.	.10	.04–.23	.4+
32	Degonia (lower)	76	tr.	23	tr.	tr.	.30	.10–.50	.7
4-300	Clore	90	4	3	3	tr.	.18	.06–.35	.4+
33	Clore (upper)	65	30	3	tr.	tr.	.10	.06–.30	.4+
34	Clore (lower)	87	4	3	2	tr.	.10	.04–.20	.4
55	Palestine	95	2	0	2	tr.	.10	.03–.25	.5
56	Palestine	91	1	3	1	tr.	.10	.04–.20	.4
4-326	Palestine (middle)	97	0	2	tr.	tr.	.20	.02–.35	.6
C1319A	Palestine	95	2	3	tr.	tr.	.25	.04–.35	.5
35	Palestine	88	10	1	1	tr.	.05	.02–.14	.3
4-334	Palestine (lower)	63	tr.	34	1	tr.	.25	.10–.60	.7+
36	Menard (upper)	75	11	10	2	1	.07	.03–.13	.4
665	Waltersburg	93	2	2	3	tr.	.16	.03–.38	.5
37	Waltersburg	75	15	5	tr.	tr.	.08	.01–.10	.4
C1488	Waltersburg	95	tr.	0	2	1	.14	.04–.34	.5
C2179	Tar Springs	80	10	1	2	1	.13	.06–.20	.6
C1803	Tar Springs	86	7	1	1	1	.15	.04–.30	.6
C1974	Tar Springs	90	6	1	1	2	.10	.05–.20	.4
C1427	Tar Springs	95	1	2	2	0	.14	.03–.21	.6
Average of 25 samples		84	7	5	2	.5	.14		.5

Location of samples:

30. Madison Coal Co. Hole No. 25, sec. 12, T. 8 S., R. 3 E., Williamson County, Ill. Depth 1802′
31. Madison Coal Co. Hole No. 25, sec. 12, T. 8 S., R. 3 E., Williamson County, Ill. Depth 1833′
32. Madison Coal Co. Hole No. 25, sec. 12, T. 8 S., R. 3 E., Williamson County, Ill. Depth 1840′
33. Madison Coal Co. Hole No. 25, sec. 12, T. 8 S., R. 3 E., Williamson County, Ill. Depth 1882′
34. Madison Coal Co. Hole No. 25, sec. 12, T. 8 S., R. 3 E., Williamson County, Ill. Depth 1910′
35. Madison Coal Co. Hole No. 25, sec. 12, T. 8 S., R. 3 E., Williamson County, Ill. Depth 1959′
36. Madison Coal Co. Hole No. 25, sec. 12, T. 8 S., R. 3 E., Williamson County, Ill. Depth 2008′
37. Madison Coal Co. Hole No. 25, sec. 12, T. 8 S., R. 3 E., Williamson County, Ill. Depth 2133′
51. Mississippi River Bluff, sec. 24, T. 8 S., R. 5 W., Jackson Co., Ill.
52. Courcier Hill, Sec. 11, T. 5 S., R. 1 W., Perry County, Indiana
53. Courcier Hill, sec. 11, T. 5 S., R. 1 W., Perry County, Indiana
54. Magnolia Oil Co.—#12 Armbruster, sec. 13, T. 7 S., R. 14 W., Posey County, Indiana. Depth 1640′
55. Mississippi River Bluff, sec. 24, T. 8 S., R. 5 W., Jackson County, Ill.
56. Creek bed, sec. 3, T. 8 S., R. 6 W., Randolph County, Ill.

4-284. New Haven Core, sec. 18, T. 7 S., R. 10 E., White County, Ill. Depth 1913′
4-300. New Haven Core, sec. 18, T. 7 S., R. 10 E., White County, Ill. Depth 1974′
4-326. New Haven Core, sec. 18, T. 7 S., R. 10 E., White County, Ill. Depth 2086′
4-334. New Haven Core, sec. 18, T. 7 S., R. 10 E., White County, Ill. Depth 2136′
665. Carter Oil Co.—#1 Fuller, sec. 11, T. 7 S., R. 8 E., White County, Ill. Depth 2166′

C1319A. Superior Oil Co.—#1A Blood, sec. 1, T. 3 S., R. 10 E., Edwards County, Ill. Depth 2176′
C1427. Adkins Oil Co.—#1 Chi., Wilmington, and Franklin Coal Co., sec. 36, T. 6 S., R. 2 E. Franklin Co., Ill. Depth 2098′
C1488. Magnolia Oil Co.—#1 Stanhope, sec. 6, T. 2 S., R. 14 W., Edwards County, Ill. Depth 2296′
C1803. Magnolia Oil Co.—#3B Rotramel, sec. 26, T. 2 S., R. 14 W., Edwards County, Ill. Depth 2186′
C1974. Texas Oil Co.—#1 Stanford, sec. 22, T. 3 N., R. 7 E., Clay County, Ill. Depth 2337′
C2179. Nat'l Assoc. Pet. Co.—#1 Sanders, sec. 33, T. 7 S., R. 9 E., Gallatin County, Ill. Depth 2310′

rocks consists of both plagioclase and potash varieties. Most of these are fresh but some show extensive kaolinitization. Several authigenic feldspar overgrowths were noted on detrital rounded grains of orthoclase.

The clay mineral fractions of these sandstones, difficult to identify precisely by ordinary microscopy, were separated from the bulk of the sand by decantation and identified by differential thermal and X-ray diffraction analysis. Illite, kaolinite, and a chloritic clay mineral were found. Illite is the most abundant clay mineral in a majority of the samples and is commonly associated with the chloritic clay mineral and, in fewer cases, with kaolinite. One sample of Degonia sandstone (sample 53) showed kaolinite in greater abundance than illite. In this sample the chloritic clay mineral is also present in small amount. A sample of Kinkaid sandstone (sample 54) showed relatively high proportions of kaolinite and chloritic clay but no illite.

The association of kaolinite with chloritic clay and the absence of illite in a calcareous fossiliferous rock such as this is somewhat anomalous under normal conditions and may indicate a source of kaolinitic material (Grim, 1951, p. 230). High relative proportions of kaolinite in association with some chlorite in these samples may indicate near-shore brackish water conditions (Glass, 1951, pp. 28–29), although it is thought that chloritic clay minerals are more characteristic of marine environments (Grim, 1951, pp. 228–9). X-ray patterns seem to indicate that some of the mica may be finely divided detrital muscovite (sericite). There is evidence from the thin-sections that some large euhedral kaolinite crytals, present in small quantity in a few samples, may be diagenetic in origin.

Although the same clay minerals, illite, a chloritic clay mineral, and kaolinite, were found in a study of Chester series shales (Grim, Bradley, and White, 1951), the relative abundances were somewhat different. In the shales chloritic clay and illite were present in higher proportions than kaolinite. This would seem to indicate that the shales sampled in this study, usually more closely associated with limestone formations, were formed in more saline waters, farther from the shore, in contrast to the more near-shore or terrestrial deposition of the sands.

Carbonate minerals, chemically precipitated rather than detrital in origin, are found in irregular patchy areas in

LEGEND FOR PLATE 1

A. Degonia (No. 32) ×100 crossed nicols. Calcareous orthoquartzite showing calcite replacing detrital quartz and euhedral secondary quartz replacing calcite.
B. Degonia (No. 32) ×100 crossed nicols. Calcareous orthoquartzite showing extensive replacement of detrital quartz by calcite.
C. Clore (No. 33) ×100, plane polarized light. Shows appearance intermediate between orthoquartzite and subgreywacke.
D. Same as C, crossed nicols.
E. Degonia (No. 52) ×100 crossed nicols. Typical subgreywacke appearance.
F. Kinkaid sandstone (No. 54) ×100 crossed nicols. Calcareous subgreywacke.

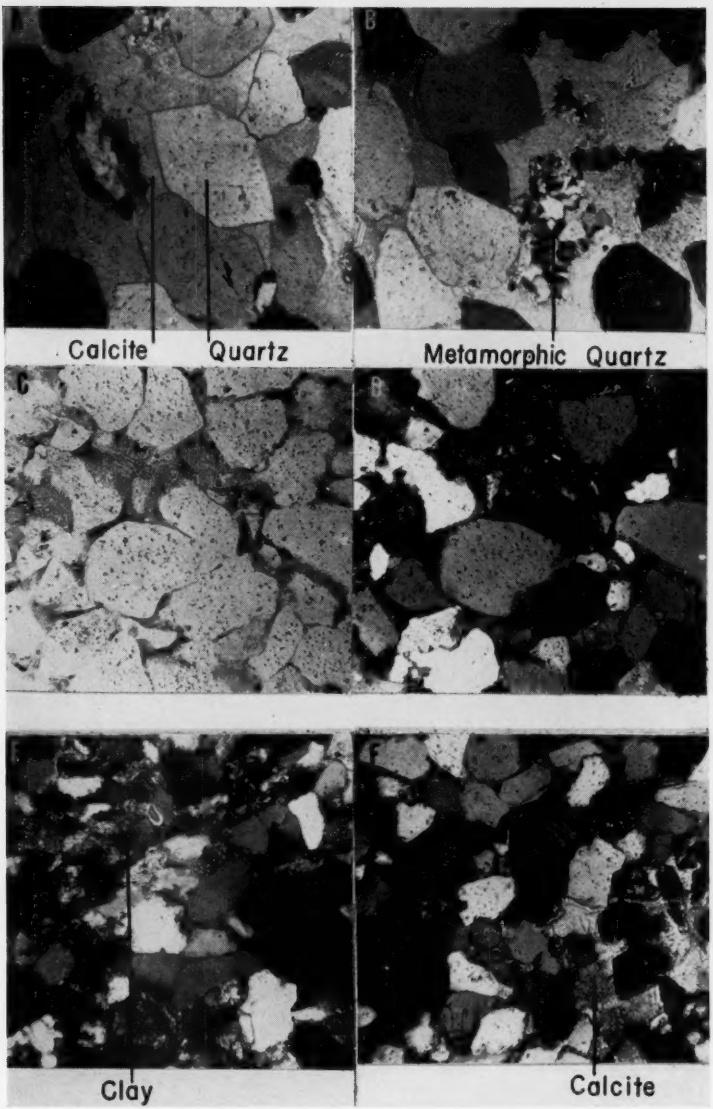

PLATE 1
Photomicrographs of Chester sandstone thin-sections.

many of the sandstones. Although most of the carbonate is calcite, some is dolomite or siderite. Carbonate occurs in the interstices and commonly replaces parts of adjacent quartz grains. Replacement phenomena, observed in thin-section, commonly follow a characteristic pattern. Carbonate replaces detrital quartz, and authigenic quartz replaces the carbonate. The chronology of cements can be interpreted from these replacements. After deposition of detrital quartz grains, calcite was precipitated in pore spaces, the calcite replacing part of the quartz. At some later time, under changed conditions, authigenic quartz was precipitated over detrital quartz grains in optical continuity with them and, in many cases, replaced some of the calcite.

Two alternative suggestions can be proposed to explain this chronology of replacement. The first is that calcite was deposited at some penecontemporaneous stage, while the unindurated sand was saturated with slightly alkaline, carbonate-saturated waters. This might be the situation while the sediment was still exposed to sea water, before burial under any appreciable thickness of later sediment. A corollary of this hypothesis would be that the amount of calcite precipitated in pore spaces would be inversely proportional to the rapidity of burial. At some later date, presumably after uplift either at the end of the Mississippian or at the end of the Paleozoic, the percolating waters changed in composition from alkaline to slightly acid, silica-saturated meteoric waters, at which time authigenic quartz was deposited and calcite was partially dissolved and replaced. The part of this hypothesis involving meteoric water infiltration should probably be rejected, partly on the evidence that the Chester sands, for the most part, contain brines that indicate that they have not been flushed out with fresh water (Meents et al., 1952).

A more reasonable hypothesis, however, can be formulated to explain the replacement of calcite by authigenic quartz. Subsequent to precipitation of calcite on the sea floor and burial by later sediment, the composition of the waters in the sediments changed, as a result of lack of free mixing with aerated sea water, from alkaline and carbonate-saturated to slightly acid and silica-saturated. According to this hypothesis both replacement phenomena would have occurred very early in the diagenetic process, as a result of very slight shifts in the composition of the entrapped sea water. Testing of these hypotheses must await further studies on modern sediments, in particular the composition of interstitial waters at depth.

Heavy minerals in these sandstones are small in amount and consist of only a few species. Some 90 per cent of the non-opaque heavy minerals are zircons and tourmalines. There seems to be little variation in these minerals other than possibly different degrees of roundness and very slight color variations. No attempt was made in this study to differentiate the zircons or tourmalines on the basis of color or roundness, although it is possible that such a study would be rewarding.

Some of the samples contain organic matter. Petroleum occurs in samples taken from oil reservoirs, and carbonaceous matter, which is macerated into minute shreds and fragments, occurs in various samples. This material is presumably derived from land plants. Further evidence of land plant activity is found in the presence of stigmarian roots preserved in sandstones in certain areas.

The average mineral composition of these rocks places them between clean orthoquartzites and average subgreywackes. Many of the samples can be classed as subgreywackes by virtue of their clay and rock fragment content. The orthoquartzite aspect of some of the samples is probably due to winnowing and reworking of sands which, when deposited originally, had a high clay content. These sands are from bars or other depositional forms such as those shown on Swann's isopach maps of the Walters-

burg sandstone in the lower Wabash River valley oil fields (1951, pp. 2568–9, 2577).

SEDIMENTATION CONDITIONS

All the characteristics of upper Chester sandstones point to an environment of deposition that varied from sublittoral turbulent waters to a terrestrial coastal plain. The abrupt facies changes from shale to sandstone, the good sorting, the cross-bedding, the evidence of winnowed and reworked sand, and the lack of fauna indicate rapid changes in direction and transporting competence of turbulent currents. The abundant kaolinite and the small amount of chloritic clay in some samples may indicate incompletely saline conditions such as would be found near shore where fresh waters mixed with sea water. Samples which contain abundant chloritic clay and little kaolinite may indicate deeper water. On the other hand, it is certain that some sands were laid down in a terrestrial environment, because they contain stigmarian roots of land plants and a few autochthonous coals beds. This evidence makes it seem probable that, during the time of Chester sedimentation, the strand line must have migrated back and forth many times.

Thus there can be no generalization concerning the marine or nonmarine origin of the sands, as strata of any one time zone may be either marine, nonmarine, or both. Sands such as the Waltersburg, which show thickness accumulations suggestive of marine current origin, are most probably marine; sands such as the Palestine, which contain abundant stigmarian roots and a thin coal bed, and which have an erosional, channeled base, are more probably terrestrial.

What clues do we have as to the source areas of the sand which makes up the deposits? The varieties of quartz give some indication. Dominantly the quartz is of igneous origin, with a lesser component of metamorphic derivation. Reworked sedimentary quartz is abundant; the roundness of the fine sand suggests that many of the quartz grains classified as igneous are actually reworked sedimentary grains. The 10 per cent content of metamorphic quartz, including lath-shaped schistose quartz and metamorphic quartzite fragments, indicates an ultimate metamorphic terrain for part of the source. The argillaceous rock fragments are mostly shales and phyllites, which would indicate no more than low-rank metamorphism of the source area. These particular varieties of quartz and their relative abundance suggest two sources for the detritus, the largest contributor being a mixed igneous and sedimentary terrain, and the secondary contributor a low-rank metamorphic terrain.

In order to determine geographically the source areas of Chester detritus we must consider the lithology of upper Chester equivalents in the Appalachian geosyncline, the Ouachita trough, and the adjoining platform areas (fig. 5). The Mauch Chunk and Pennington formations, the upper Chester equivalents in Pennsylvania and West Virginia, contain some coarse clastic material, but are composed chiefly of shale and silt on the western side of the geosynclinal axis. The Leitchfield formation, which crops out on the western flank of the Cincinnati arch in the easternmost extension of the Eastern Interior Basin, consists almost entirely of limestone and shale and contains only very subordinate amounts of silt and fine sand. In the southern Appalachians, upper Chester equivalents contain less coarse clastic material than shale and limestone. Recent subsurface investigations seem to indicate that there is no great thickness of sandstone in the upper Chester equivalents in northeastern Mississippi.

On the western side of the Mississippi embayment, we find that the upper Chester correlatives on the south flank of the Ozarks, the Fayetteville and Pitkin formations, with the exception of the Wedington sandstone member of the Fayetteville, do not have any significant proportion of coarse clastics. Farther southwest in the Ouachitas, Chester

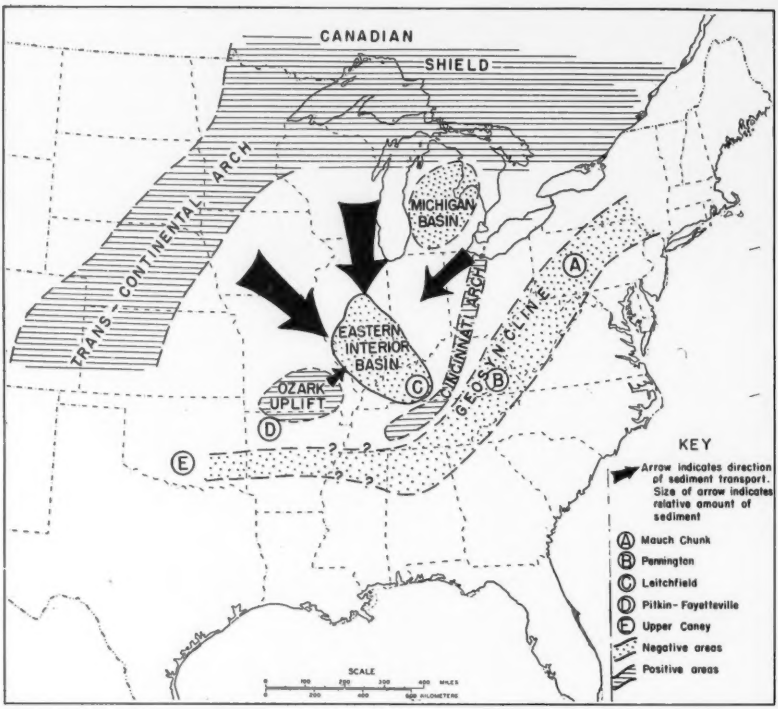

FIG. 5.—Paleogeographic map of upper Chester time.

rocks, the upper Caney and possibly part of the Stanley, are also dominantly fine clastics, although there is a great thickness of greywackes in the Stanley (Bokman, p. 154, 1953) of Oklahoma and Arkansas.

Thus all through the Appalachian geosyncline and in the areas immediately to the west of the downwarp, the outstanding feature of the upper Chester rocks is that they do not contain much sandstone. In those areas of the Ouachitas where there is a great amount of coarse clastics, they are of a greywacke type and not at all similar to the Chester sandstones of Illinois. It is exceedingly doubtful that detritus of greywacke composition would change to detritus of orthoquartzite composition in the course of a few hundred miles of transport, and therefore it is improbable that Illinois Chester sands were derived from the same areas as lower Stanley greywackes.

The only area aside from Illinois where there may be any great thickness of sandstone of Chester age is in northern Mississippi and Louisiana where Chester strata are deeply buried. This may have been a route through which coarse detritus passed en route to the Eastern Interior Basin, but data are not sufficient to test this possibility. A suggestion that sediments followed any other route to the basin from source areas to the east or south would require that coarse clastics by-passed the geosynclinal downwarps and fine clastics were deposited in them.

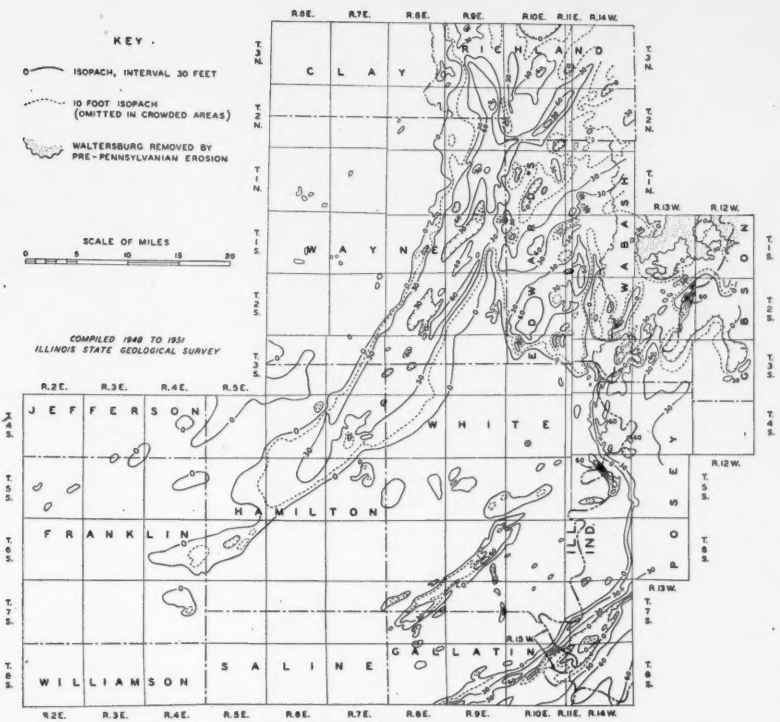

FIG. 6.—Thickness of permeable sand in Waltersburg formation of central Illinois basin (from Swann, 1951).

This explanation runs counter to any normal conditions of sediment transport and deposition. Hence, it is proper to consider the possibility of northern sources within the continent for Chester clastic materials.

One of the first to propose a transcontinental arch, or "Continental backbone," and the Canadian shield as sources for sediments was Levorsen (1931), in his discussion of basal Pennsylvanian sediments. The idea of the arch, unpopular at first, has now been accepted by Eardley (1949), King (1951, p. 30), and others. Reed (1948) has demonstrated the existence of this broad low arch, passing from Minnesota through central Nebraska and farther south, which never received any Mississippian sediment. Petrographic evidence that Chester sands were derived in large part from pre-existing sediments makes the lower and middle Paleozoic sediments of the transcontinental arch and the Canadian shield likely sources for much of the detritus.

The abundant metamorphic quartz and quartzite in the Indiana samples suggest that there may have been some contribution of this material from the northeast. This area would roughly coincide with the general area which supplied much of the clastic material to the Greenbrier formation in West Vir-

ginia, lower in the Mississippian section (Rittenhouse, 1949, p. 1723). It is interesting, in this connection, to note the isopach map of the Waltersburg sand drawn by Swann (1951) (fig. 6). This map shows several long narrow sand bodies trending northeast-southwest and a broader, more uniformly thick area to the east and north of the linear sand bodies, in Richland, Edwards, and Wabash counties. The thickness distribution of this sand, when considered in the light of probable source areas, suggests that the elongate sand bodies represent accumulations in marine currents that trended roughly transverse to the shoreline; the shoreline trended more or less parallel to the more uniformly thick sand area to the north and east. The latter area was probably the site of near shore deposition, where one could expect to find offshore bars parallel to the shoreline, north-northwest–south-southeast.

TECTONICS

It is important to summarize the tectonics of the basin of deposition which exercised some control on the kind of sediment laid down. During late Mississippian time the Eastern Interior Basin sank slowly and intermittently. Downwarping was more or less uniform as evidenced by generally similar Chester thickness throughout the basin.

However, there were local incipient positive areas at this time, such as the Salem-Louden anticline, the Clay City-Noble anticline, and other smaller anticlinal structures. The presence of these incipient structures, which were more strongly folded in post-Pennsylvanian time, has been amply demonstrated by subsurface investigations in Illinois. While the subsidence of the basin provided the over-all control on sedimentation, these smaller positive areas exercised some local control. Thus, we find that the total section of many formations thins slightly over the structures. In some places, sandstones are more winnowed and reworked over the structures. The more reworked character of the sands as well as the greater thickness of sand on the structure, noted in several areas, implies that the incipient structures were expressed topographically. The topographic expression caused more turbulence in the water, and the currents were more competent to transport coarse-grained material, which resulted in better sorting of the coarse clastics. In general, the structures were too small to influence sedimentation over a large area.

The petrographic nature of these sandstones, orthoquartzites, subgreywackes, and washed subgreywackes, implies only moderate deformation of the source area. The lack of appreciable quantities of feldspar, the sedimentary varieties of quartz, the fine-grained, rounded, and well-sorted detritus indicate that land areas were not subject to rapid and rigorous erosion and that they were still largely covered by a thin sedimentary mantle. The evidence points to a condition of only moderate uplift, perhaps accompanied by slight deformation.

It is hoped that, in the future, detailed, quantitative petrographic studies of Chester rocks in other areas will be made and correlated with detailed stratigraphic information. Through such studies will come a fuller understanding of the paleogeography, the sedimentation conditions, and tectonic controls under which these rocks were laid down.

REFERENCES

BOKMAN, J. (1953) Lithology and petrology of the Stanley and Jackfork formations: Jour. Geology, vol. 61, pp. 152–170.

EARDLEY, A. J. (1949) Paleotectonic and paleogeologic maps of central and western North America: Am. Assoc. Petroleum Geologists Bull., vol. 33, pp. 655–682.

GLASS, H. D. (1951) Clay mineralogy of the Coastal Plain formations of New Jersey: Unpublished Ph.D. thesis, Columbia University.

GRIM, R. E. (1951) The depositional environment of red and green shales: Jour. Sedimentary Petrology, vol. 21, pp. 226–232.

GRIM, R. E., BRADLEY, W. F. and WHITE, W. A. (1951) Petrology of the Paleozoic shales of Illinois: Geol. Soc. America Bull., vol. 62, p. 1445.

KING, P. B. (1951) The tectonics of middle North America: Princeton Univ. Press.

KRUMBEIN, W. C. (1941) Measurement and geological significance of shape and roundness of sedimentary particles: Jour. Sedimentary Petrology, vol. 11, pp. 64–72.

LEVORSEN, A. (1931) Pennsylvanian overlap in the United States: Am. Assoc. Petroleum Geologists Bull., vol. 15, pp. 113–148.

MEENTS, W. F., BELL, A. H., REES, O. W. and TILBURY, W. G. (1952) Illinois oil field brines: Illinois Geol. Survey, Ill. Petroleum No. 66.

PETTIJOHN, F. J. (1949) Sedimentary rocks, New York, Harper and Bros.

REED, E. C. (1948) The possibility of a land bridge across Nebraska in Mississippian time: Jour. Geology, vol. 56, pp. 308–312.

RITTENHOUSE, G. (1949) Petrology and paleogeography of the Greenbrier formation: Am. Assoc. Petroleum Geologists Bull., vol. 33, pp. 1704–1730.

SWANN, D. H. (1948) Facies relations of Upper Chester formations of Illinois basin: Geol. Soc. America Bull., vol. 59, p. 1356.

——— (1951) Waltersburg sandstone oil pools of lower Wabash area, Illinois and Indiana: Am. Assoc. Petroleum Geologists Bull., vol. 35, pp. 2561–2581.

WELLER, J. M. (1930) Cyclical sedimentation of the Pennsylvanian period and its significance: Jour. Geology, vol. 38, pp. 97–135.

WELLER, J. M. and SUTTON, A. H. (1940) Mississippian border of Eastern Interior Basin: Am. Assoc. Petroleum Geologists Bull., vol. 24, pp. 765–858.

WELLER, S. (1920) The Chester series in Illinois: Jour. Geology, vol. 28, pp. 281–303, 395–416.

WORKMAN, L. E. (1940) Subsurface geology of the Chester series in Illinois: Am. Assoc. Petroleum Geologists Bull., vol. 24, pp. 209–236.

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FIGS. 1–4, DECEMBER, 1953

FACIES INDICATORS IN THE UPPER PENNSYLVANIAN OF SEMINOLE COUNTY, OKLAHOMA[1]

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ABSTRACT

Upper Pennsylvanian beds of Seminole County, Oklahoma, exhibit characteristics of three distinctive facies. These are interpreted as the products of the following environments: lagoon or tidal flat; beach or barrier island; and shallow, near-shore marine. Indicators of these facies are discussed.

INTRODUCTION

The field work on which this paper is based was carried out in Seminole and five adjacent counties of Oklahoma (fig. 1) in the summer of 1951. The work involved preparation of a set of township plats, at a scale of approximately three inches to the mile. For this purpose air photographs, flown in 1938, were used. In addition to mapping from the air photos, the author measured 260 lithologic sections; described lateral lithologic variations in detail; made extensive fossil collections; analyzed a number of limestone, sandstone and conglomerate samples; examined various potential sediment source areas; and studied several hundred electric logs in the immediate area.

Seminole County covers about 700 square miles, located, roughly, between 35° and 35°30′ north, and between 96°30′ and 97° west. The center of the county is about 60 miles southeast of Oklahoma City, and about 80 miles southwest of Tulsa (airline distances).

The Arbuckle Mountain-Hunton Arch complex lies only a few tens of miles to the south.

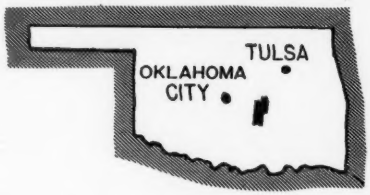

FIG. 1.—Map of Oklahoma, showing the location of Seminole County.

STRATIGRAPHIC SEQUENCE

The stratigraphic column in Seminole County comprises deposits of Pennsylvanian, Permian and Quaternary age. Rocks of the Pennsylvanian system include the following series and formations:

Virgil series:
- Vanoss
- Ada
- Vamoosa

Missouri series:
- Hilltop
- Belle City
- Nellie Bly } Francis
- Coffeyville }
- Seminole

Des Moines series:
- Holdenville
- Wewoka

[1] Condensed from "The Geology of Seminole County, Oklahoma," a dissertation submitted to the faculty of the University of Oklahoma in partial fulfillment of the requirements for the Ph.D. degree.

The author wishes to express his appreciation to George G. Huffman, of the university faculty, who supervised the project; to Malcolm Oakes, of the Oklahoma Geological Survey, who checked the field map; to W. D. McBee, independent geologist, who contributed greatly to the understanding of the subsurface data; and to the Oklahoma Geological Survey, which furnished the air photographs and employed the writer for one field season.

A single Permian formation—the Konawa—is exposed in a strip along the western boundary of the county.

The strike varies from about N. 20° E., in the southeastern part of the county to almost due north, in the western part of the county. The average dip is about 90 feet per mile, to the west.

Two major and many lesser unconformities appear within the sequence. The most significant unconformities are (1) at the base of the Vamoosa formation (i.e., at the base of the Virgil series), and (2) at the base of the Ada formation (in the upper third or upper half of the Virgil series). In terms of section cut out, the unconformity at the base of the Ada is by far the more important, for it truncates seven formations (Pawhuska, Vamoosa, Hilltop, Belle City, Nellie Bly, Coffeyville and Seminole) in Okfuskee, Seminole and Pontotoc counties. In a linear distance of about 60 miles, roughly 2,100 feet of section has been cut out. The average angle of truncation is five to 10 feet per mile; other, lesser unconformities account for the over-all discrepancy. The basal Ada truncation represents the last important uplift in the Hunton arch to the south; this took place about the middle of Virgil time.

The unconformity at the base of the Vamoosa formation possesses much greater local relief (i.e., up to 200 feet in 15 miles) and a much lower angle of truncation. Within the county, only the Hilltop formation is cut out, and it reappears in a short distance.

The unconformity at the base of the Seminole formation is not easily demonstrable within the county; convincing evidence for it must be sought in Pontotoc County, to the south; or in Tulsa County, 80 or 90 miles to the northeast (Oakes, 1952). In both areas, the Holdenville formation is overlapped.

Several minor unconformities, most of them with truncation ratios less than 10 feet per mile, have been found. These occur within the Seminole and Vamoosa formations, and at the base of the Vanoss formation.

The chronology deduced from these unconformities is that of a sequence of pulsations in the Arbuckle Mountain-Hunton Arch area in Missouri and Virgil time. There is no evidence for orogeny in this area at the close of the Pennsylvanian.

In addition to middle and late Pennsylvanian diastrophism in the Arbuckle Mountains, the rocks were tilted westward, in Permian time, by the Ouachita Mountain folding to the east. This later tilting accounts, at least in part, for the regional westward dip and the consequent exposure of the section given above.

The rocks are predominantly shale. Shale: sandstone ratios are on the order of 60:40 to 90:10, the larger proportions of shale occurring in the northern part of the county. In addition to the shales, sandstone and siltstone ledges, rarely as much as 50 feet thick, are found at regular intervals throughout the section. Chert conglomerates, limestone conglomerates and arkose conglomerates are easily found, although they make up only a small fraction of the total sequence. Limestones are thin and widely-spaced, and of several varieties. Totalling less than one per cent of the section are rarer lithologies such as biotite sandstone, hematite sandstone, and clay-plate conglomerate.

Many of the so-called limestones are actually thoroughly recemented sandstones: chemical analysis indicates more than 60 per cent insoluble residues. Some of the true limestones are described briefly below.

Three facies are developed in Seminole and adjacent counties. They are interpreted as products of the following environments:

1. Lagoon or tidal flat.
2. Barrier island or beach.
3. Nearshore marine.

In general, the lagoon facies is developed in the central or southern parts of the county, and the nearshore marine facies in the central or northern parts of the county. The barrier island facies is

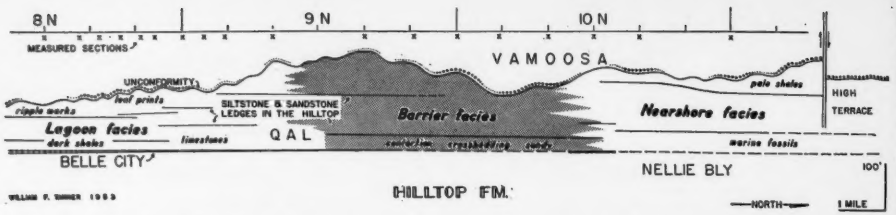

FIG. 2.—The three facies of the Hilltop formation, with evidences for each. Northward the Hilltop grades into regularly-bedded marine shales, sandstones and limestones. Southward it is truncated by the overlying Vamoosa conglomerate. The underlying Nellie Bly exhibits the same three-fold development: in Okfuskee County, to the north, evenly-bedded alternating marine shales and sandstones; in northern Seminole County, sandy, contorted and cross-bedded barrier deposits; and in southern Seminole County, dark calcareous shales, thin limestone lenses and restricted fossil suites. Other late Pennsylvanian formations in Seminole County show similar gradations.

neither as clearly defined nor as wide as either of the other two facies.

KEY LIMESTONE BEDS

The best key beds in the county are the Homer and Sasakwa limestone members of the Holdenville formation, the DeNay limestone member at the base of the Coffeyville, and the Belle City limestones. Each of these passes northward into a shale, sandy shale or sandstone section; no one of them is correlated positively northward with any known marine limestone, although the DeNay occurs approximately at the horizon of the Checkerboard limestone of north central Oklahoma and the Belle City is not far from the horizon of the Dewey limestone.

Behaving in a similar manner is the Hart limestone member, at the base of the Permian system, in Pontotoc County to the southwest. In addition to these six named limestones, there are many unnamed limestone lenses which also pass northward into clastic units.

Dimensions for the key beds are:

	Length of outcrop (miles)	*Thickness (maximum)*	*Ratio*
Upper Belle City	35	11′	16,800:1
Lower Belle City	25	3′	44,000:1
DeNay member	30	5′	31,680:1
Sasakwa member	25	15′	8,800:1
Homer member	25	10′	13,200:1

The bedding is thin and regular, with wavy contacts prominent in the Belle City formation and the Sasakwa member. Individual beds within the DeNay are about one foot thick, but in places are thinner; in the other key limestones, individual beds are, at most places, only a few inches thick.

The Sasakwa limestone member contains at least 50 invertebrate species, indicating free circulation of marine waters. The Homer limestone member is characterized by *Fusulina* faunules in Pontotoc County (to the south), *Chaetetes* faunules near the Pontotoc-Seminole county line, and pelecypod faunules in Seminole and western Hughes counties (to the north). Identifiable species are rare, however. The Belle City formation yields a limited suite of numerous, robust brachiopods. The DeNay limestone member possesses a rather restricted fauna (12 species) including trilobites and punctate brachiopods.

The ratios given above, the thin bedding, and the relative scarcity of fossils (other than in the Sasakwa) do not support the concept that these are reef limestones. The fact that they pass northward into shale or sandstone suggests that they are not open marine deposits. A lagoon environment seems to be indicated. The key beds do not, however, contain the best evidence for such an environment.

LAGOON AND TIDAL FLAT FACIES

The Coffeyville, Nellie Bly, Hilltop, Ada and Konawa formations are marked, locally, by shale and limestone sequences of a distinctive nature. A good example is the Hilltop shale exposed in and near the Wewoka Brick and Tile Company pit (sec. 11, T. 8 N., R. 7 E.). These shales are blue-gray. They alternate with tan or buff siltstones and dense gray or blue-gray limestones; the siltstones and limestones are, in most places, only an inch or two thick. Carbon films occur in the shales. Ripple marks are common, leaf prints may be found, and poorly-preserved brachiopods and pelecypods are rare in the siltstones. The limestones are crystalline.

Within this facies, the shales probably make up more than 75 per cent of the section. In each formation named above, the shale-and-limestone sequence grades northward into sandstone or sandy shale (described below).

During Missouri and Virgil time, the early-to-middle Paleozoic limestones of the Hunton arch were exposed five to 20 miles to the south. Dott (1930), using a mechanism suggested by Clarke (1924), considered this situation ideal for the development of lagoons. The low truncation angles reported above indicate a coastline without great relief, and shallow waters for some appreciable distance off-shore. This structural fact is accepted as support for Dott's hypothesis. The dark blue-gray and gray shales are interpreted as tidal flat deposits, and the thin limestones as the product of a lagoon type environment (fig. 2). The key limestone beds listed in an earlier section are thought to be atypical lagoon deposits.

BARRIER ISLAND AND BEACH FACIES

The Holdenville, Seminole, Coffeyville, Nellie Bly, Hilltop, Vamoosa, Ada and Konawa formations are marked locally by clastic phases having certain distinctive characteristics. Conglomerate and sandstone lenses are prominent, and the shales are either red or sandy. Fossils are rare, and may be *Calamites* or *Lepidodendron*. *Neospirifer dunbari* King, a large, thick-shelled brachiopod, has been collected from this facies.

Coarse conglomerates, containing chert, limestone, feldspar, sandstone, siltstone or other pebbles, are not continuous toward the source. In the Seminole, Nellie Bly, Vamoosa, Ada and Konawa formations, the coarsest conglomerates occur in what appear to be isolated lenses located some distance northward from the postulated shore. In each instance, the average particle size, as well as the maximum particle size, decreases, along the strike, both to the north and to the south. A good example of this may be found in the Vamoosa formation, in which pale chert cobbles up to seven inches in diameter occur (T. 10 N.). In southern Seminole County (T. 5 N.) and northern Pontotoc County (T. 5 N.) the maximum size is about five inches. The same thing is true of the dark chert conglomerates in the Konawa formation, near Dripping Springs (T. 8 N.).

Oakes (1948) interpreted the pale chert conglomerates as evidence for a westward-flowing river which channeled across the various formations listed above. The cherts, however, do not seem to have a source to the east; in fact, identical cherts are plentiful within the early and middle Paleozoic limestones in the Arbuckle Mountain-Hunton arch area to the south; and Miser (1952) does not recognize the common, pale cherts as Ouachita Mountain types.

Fortunately, the pebbles are not limited to pale and dark cherts. In addition they are lavender feldspar (apparently derived from the Tishomingo granite, about 50 miles to the south) in the Vanoss formation; limestone cobbles and boulders (derived from the early and middle Paleozoic formations of the Hunton arch) in the Ada and other formations; and brecciated cherts (derived, probably, from tectonic breccias in the Mill Creek syncline, 40 or 50 miles to the southwest) in the Vamoosa formation. With one exception, each of these conglomerates possesses a zone of maximum particle

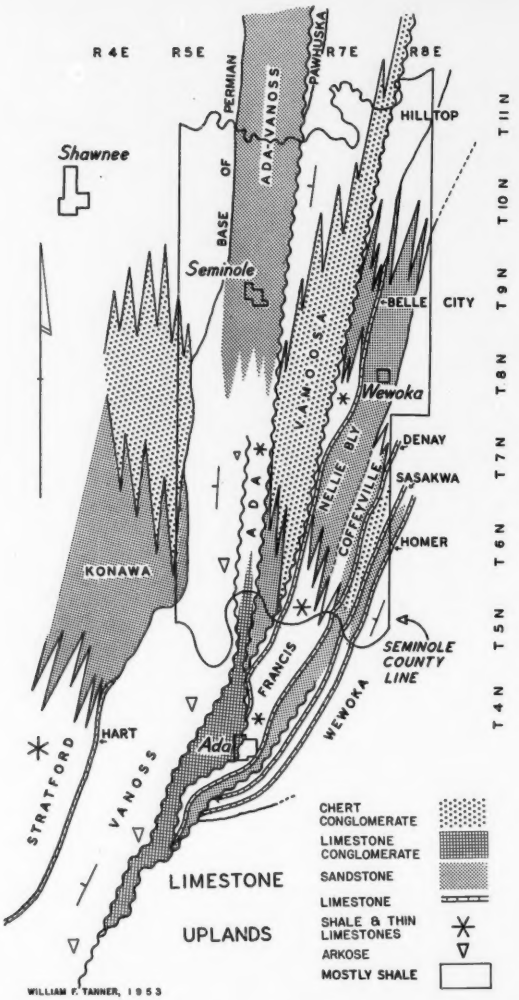

FIG. 3.—Diagrammatic representation of the facies of the Permo-Pennsylvanian section of Seminole and adjacent counties. Much—but not all—of the unmarked area consists of regularly-bedded alternating shales and sandstones. Four unconformities are shown: those at the bases of the Seminole, Vamoosa, Ada and Vanoss formations. No effort has been made to show all lithologies; for instance, the distinctive basal Ada sandstone has been omitted, sandy shales in several formations have been shown as sandstone, and a number of unnamed lenticular limestones and limestone conglomerates have been left off. Topographic effects have been smoothed out to a large degree.

diameter, from which both the average and maximum particle sizes decrease in both directions. If westward-flowing rivers deposited in their channels layers of chert gravel obtained from the east, a similar source should be sought for the arkoses, limestone conglomerates and tectonic breccias. The character of these conglomerates, however, is not that of channel-deposits; they are lenses only by measurement, and not by observation, having width-depth ratios on the order of 5,000:1. This is much too wide and shallow for stream channels.

Penecontemporaneous contortion is found in many of the beds within the county. In each instance the beds dip gently westward (about 90 feet per mile), yet clinometer readings on individual layers within the beds may show values up to and beyond 90 degrees. Crumpling, buckling and "churning" effects have been noted in these contorted strata. Following Emery (1950) and Thompson (1951), these strata are interpreted as beach sands. Clino deposits (Rich, 1951) have been described as having such contortions. In support of the beach interpretation may be marshalled the following facts: medium sands as well as silts are involved; several contorted members are basal or overlapping sandstones; cross-bedding, torrent-bedding and ripple-marking are common; plant fossils are present; the southern shore was only a few miles distant; and the low initial dips did not permit great water depths.

The best example of penecontemporaneous contortion occur in the Seminole, Hilltop, Vamoosa and Ada formations. The Hilltop contorted sands grade southward into the lagoon-and-tidal-flat shales described above. The Ada contorted sandstone is the basal member, which lies unconformably on beds of Cambro-Ordovician, Missouri and Virgil age. The Seminole contorted sandstones are involved in lesser truncations.

Sandstone samples, especially from the Vamoosa formation, were analyzed for sorting coefficients (Pettijohn, 1949) and median diameters. Results from six representative samples are listed below:

Sorting coefficients	*Median diameters*
1.350	0.305
1.330	0.200
1.210	0.185
1.205	0.230
1.200	0.165
1.175	0.250

Beach sands are reported to have sorting coefficients in the range 1.2 to 1.6, less commonly to 2.4 (Emery and Stevenson, 1950). A study of Recent Oklahoma river sands revealed sorting coefficients ranging from 1.15 to 1.60 (Tanner and Mallams, 1950). Sorting of sand dunes is in the same range (Sidwell and Tanner, 1939).

Bagnold curves (Bagnold, 1941, p. 118, ff.) indicate that the degree of sorting has been impaired, in some instances, by the addition of significant proportions of fines, and hence that the original sorting was even better than that given above. Rounding curves (Tanner, 1940) suggest that some of the sand may have been wind-handled through part of its history.

Considering the median diameters given above, as well as the other data, the beach environment seems to be indicated.

Ripple marks are especially well developed in, although by no means limited to, the Nellie Bly formation. In every instance, the ripple index is approximately nine or ten. Oscillation ripple marks trend roughly N. 20° W., and N. 40° E. to N. 50° E. Asymmetrical ripple marks were developed as a result of currents flowing, locally, in two different directions: ripples trending N. 60° E. were formed by currents flowing from the southeast; and ripples trending N. 10° W. to N. 15° W. were due to currents flowing from the northeast. Longshore currents may have formed some of these ripple marks.

NEARSHORE MARINE FACIES

Strata here assigned to an open-sea environment are more-or-less regularly bedded sequences of sandstone and light-colored shales. Individual ledges may be traced for long distances; conglomerates are rare; and marine invertebrate fossils are common. Examples occur in the

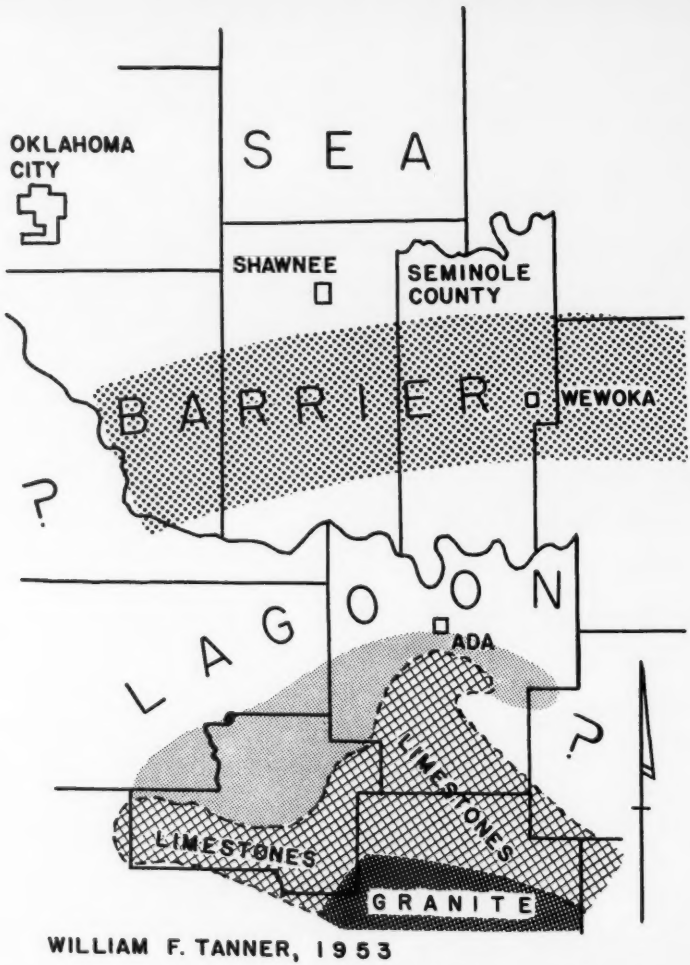

FIG. 4.—The southeastern part of central Oklahoma, showing Seminole County, the Hunton arch (south of Ada) and the Arbuckle Mountains (southwest of Ada). A generalized paleogeography of late Pennsylvanian time is indicated; included are open sea, barrier island, lagoon and tidal flat, and sediment source areas. The barrier was probably not as straight as is shown, and oscillated between limiting positions in the northern and southern parts of Seminole County. Lagoonal limestones now exposed in the area are generally found south of the latitude of Wewoka.

Wewoka, Holdenville, Seminole, Coffeyville, Nellie Bly and Hilltop formations. Ries (1951), after working in Okfuskee County to the north, reported the follow-

ing numbers of species:

Dewey limestone (lower Hilltop):	40
Nellie Bly:	19
Coffeyville:	66
Seminole:	52
Holdenville:	98
Wewoka:	103

In Seminole County, the Wewoka yielded only 21 species, the Seminole only 13 species, and the Hilltop only five species.

The Hilltop formation contains good examples of all three facies. In the northeastern part of Seminole County (T. 9 N., T. 10 N.), it is sandy, contorted, crossbedded and barren (fig. 2). South of that area the Hilltop is characterized by the shale-and-limestone sequence here interpreted as the product of a lagoon or tidal flat environment. North of that area the Hilltop is marked by the regularly-bedded sandstones and light-colored shales here assigned to the nearshore marine environment.

The Nellie Bly formation likewise contains good examples of all three facies. The barrier lay between T. 5 N. and T. 10 N., but probably was not at any time as much as 25 miles wide. North of T. 10 N., the Nellie Bly is regularly-bedded; Ries (1951) was able to trace 12 of 13 members completely across Okfuskee County, whereas only one of these is continuous across Seminole County. South of the barrier (T. 4 N., T. 5 N.) the Nellie Bly contains a sequence of thin limestones and dark shales.

Not all of the lithologies of Seminole County can be placed in one of the three facies described above. One of the limestone conglomerates appears to have been more-or-less continuous toward its source, and may have been the product of erosion following normal faulting in the Hunton arch area. In general, however, each of the formations includes one or more of these three facies.

PALEOGEOGRAPHY

Most of the limestones here interpreted as lagoonal are too thin to be traced with any confidence in the subsurface. Thicker limestones, such as the Belle City, apparently extend westward (i.e., down dip) for great distances. The present outcrops seem to cut across rather than along such beds. Structural calculations indicate that shoreline trends extend, roughly, in an east-west direction. Truncation lines and isopach maps support these calculations. The generalized paleogeography of the area in late Pennsylvanian time shows the Hunton arch and Arbuckle Mountains exposed in an east-west line, south of the seaway. This also suggest an east-west shoreline trend.

It is true that this postulated shoreline lies at right angles to the present strike of the beds, and hence that the present dip and the initial dip are at right angles to each other. This fact, however, in no way detracts from the interpretation here given (Anderson, 1941; Melton, 1947).

Environments during Missouri and Virgil time no doubt shifted irregularly, and hence no single map will be accurate for the span of two epochs. However, a representative paleogeographic map may be drawn for the late Pennsylvanian; such an interpretation is shown in figure 4.

REFERENCES

ANDERSON, G. E. (1941) Origin of line of color change in red bed deposition: Geol. Soc. America Bull., vol. 52, pp. 211–218.

BAGNOLD, R. A. (1941) The physics of blown sand and desert dunes, Methuen and Co., Ltd., London, 265 pp.

CLARKE, F. W. (1924) The data of geochemistry: U. S. Geol. Survey Bull. 770, p. 131.

DOTT, ROBERT H. (1930) Garvin county: Oklahoma Geol. Survey Bull. 40, vol. 2, pp. 119–143.

EMERY, K. O. (1950) Contorted Pleistocene strata at Newport beach, California: Jour. Sedimentary Petrology, vol. 20, pp. 111–115.

EMERY, K. O., and STEVENSON, R. E. (1950) Laminated beach sand: Jour. Sedimentary Petrology, vol. 20, pp. 220–223.

GREEN, DARSIE A. (1936) Permian and Pennsylvanian sediments exposed in central and west-central Oklahoma: Am. Assoc. Petroleum Geologists Bull., vol. 20, pp. 1454–1475.

MELTON, FRANK A. (1947) Onlap and strike overlap: Am. Assoc. Petroleum Geologists Bull., vol. 31, pp. 1868–1878.

MORGAN, GEORGE D. (1924) Geology of the Stonewall quadrangle, Oklahoma: Oklahoma Bur. Geology Bull. 2.

OAKES, MALCOLM C. (1948) Chert river, an inferred Carboniferous stream of southeastern Oklahoma: Oklahoma Acad. Sci. Proc., vol. 28, p. 70.

——— (1951) The proposed Barnsdall and Tallant formations in Oklahoma: Tulsa Geol. Soc. Digest, vol. 9, pp. 119–122.

——— (1952) Geology and mineral resources of Tulsa County, Oklahoma: Oklahoma Geol. Survey Bull. 69, Plate I.

PETTIJOHN, F. J. (1949) Sedimentary rocks: Harper & Bros., New York, p. 23.

RICH, JOHN (1951) Three critical environments of deposition and criteria for recognition of rocks deposited in each of them: Geol. Soc. America Bull., vol. 62, pp. 1–20.

RIES, EDWARD R. (1951) The geology of Okfuskee County, Oklahoma: unpublished doctoral dissertation, Univ. of Oklahoma.

SIDWELL, RAYMOND, and TANNER, W. F. (1939) Sand grain patterns of West Texas dunes: Am. Jour. Sci., vol. 237, pp. 181–187.

TANNER, W. F. (1940) An electrical method for the identification of sands: Am. Jour. Sci., vol. 238, pp. 42–46.

TANNER, W. F. and MALLAMS, PAULA (1950) Sorting of Canadian River, Oklahoma, sands: Jour. Sedimentary Petrology, vol. 20, pp. 224–226.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 23, NO. 4, PP. 229–234
FIGS. 1–5, DECEMBER, 1953

SHELL ACCUMULATIONS IN UNDERWATER SEDIMENTS AND THEIR RELATION TO THE THICKNESS OF THE TRACTION ZONE[1]

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ABSTRACT

Megascopic examination of several hundred cores taken in the Chesapeake Bay and on the adjacent Continental Shelf has shown that many sand cores from the shelf show a preferred depth of accumulation of large shells and pebbles while cores from inside the Bay usually do not. The hypothesis that the preferential sorting of large sized particles in sand cores is accomplished by swell is advanced. Observations which suggest the way the mechanism provided by passing swell operates are described. The importance of the hypothesis to paleontology and sedimentary geology is briefly discussed.

INTRODUCTION

The Chesapeake Bay Institute has taken several hundred cores in the Chesapeake Bay, its estuaries, and on the adjacent Continental Shelf. It is hypothesized that passing swell brings about the vertical sorting found in some of these cores. Since the authors lay no claim to having worked out all the consequences of this hypothesis, the purpose of this paper is to describe some observations made from megascopic logs of cores and a limited amount of laboratory work, and to offer an explanation based on the new hypothesis in the hope that other geologists will be sufficiently interested to check the hypothesis wherever possible.

OBSERVATIONS

Megascopic examination has shown that where shell matter and gravel occur in sandy shelf cores there is usually for each core, a preferred depth of accumulation. Out of 100 cores from the shelf which contained less than 5 per cent silt and clay, 50 were randomly selected, and of these 76 per cent showed preferential accumulation.

Typically, there is a fairly sharp break in the shell and gravel content separating an upper (traction) zone ranging in thickness from 0 to 6 feet and containing only a few shells and little gravel from a deeper (accumulation) zone containing relatively many more shells and much gravel. Cores have penetrated as much as eight feet into the lower accumulation zone, but in no case has a core passed through this layer into a different sediment.

All of the cores suggest a shell orientation *in situ* ranging from random to possibly vertical although orientation may be disturbed in taking the core. The shells, usually broken, are dominantly those of pelecypods, gastropods, corals, and bryozoans. The same sorts of shells are found throughout the core. The micro-fauna are far more abundant in the upper or traction zone.

In the accumulation zone the gravel content usually increases. In many cores the change in grain size from the traction to the accumulation zone is from very fine to coarse sand, in others it is from coarse sand to gravel. The important thing is the relative grain size in the two zones.

[1] Contribution No. 9 from the Chesapeake Bay Institute.

Results of work carried out for the Office of Naval Research of the Navy Department and the U. S. Navy Hydrographic Office under contract with The Johns Hopkins University.

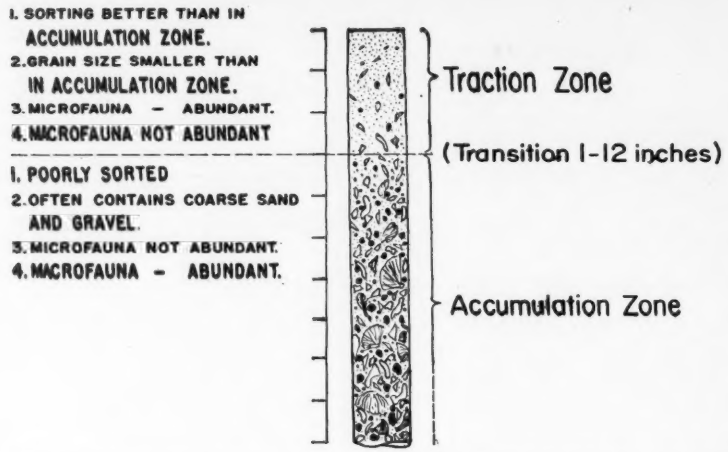
1. SORTING BETTER THAN IN ACCUMULATION ZONE.
2. GRAIN SIZE SMALLER THAN IN ACCUMULATION ZONE.
3. MICROFAUNA – ABUNDANT.
4. MACROFAUNA NOT ABUNDANT
1. POORLY SORTED
2. OFTEN CONTAINS COARSE SAND AND GRAVEL.
3. MICROFAUNA NOT ABUNDANT.
4. MACROFAUNA – ABUNDANT.
Traction Zone
(Transition 1-12 inches)
Accumulation Zone

FIG. 1.—Schematic representation of large particle distribution in a core showing traction and accumulation zones.

The grading from the traction zone sediment containing a finer grained, scarcer, and smaller macro-fauna, and more abundant micro-fauna to the accumulation zone sediment containing a coarser, more abundant, and larger macro-fauna, and scarcer micro-fauna takes place vertically in 1 to 12 inches.

Figure 1 illustrates the relations of of grain size and shell content to depth in a core. Figure 2 is a photograph of a core showing the same relations. Figure 3 shows the change in concentration of the particles greater than 2.0 mm with depth in the core for four representative cores.

A most important series of observations relates the grain size in the traction zone to its thickness. Where coarse sands form the mode in the traction zone, it is quite thick, sometimes as much as 6 feet. The traction zone becomes thinner as grain size decreases. Figure 4 suggests this trend, although it is based on a limited number of observations. Very poorly sorted sediments seem to have thinner traction zones than better sorted sediments.

None of the phenomena described so far has been seen in cores containing enough clay and silt to form a mud when wet.

It seems significant that while traction

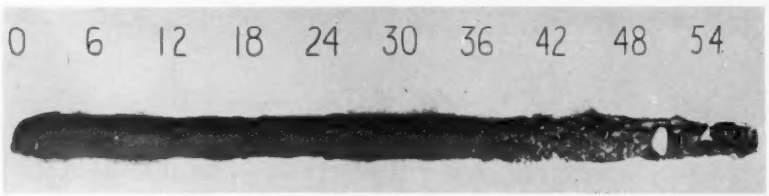

FIG. 2.—Photograph of a typical core showing traction and accumulation zones.

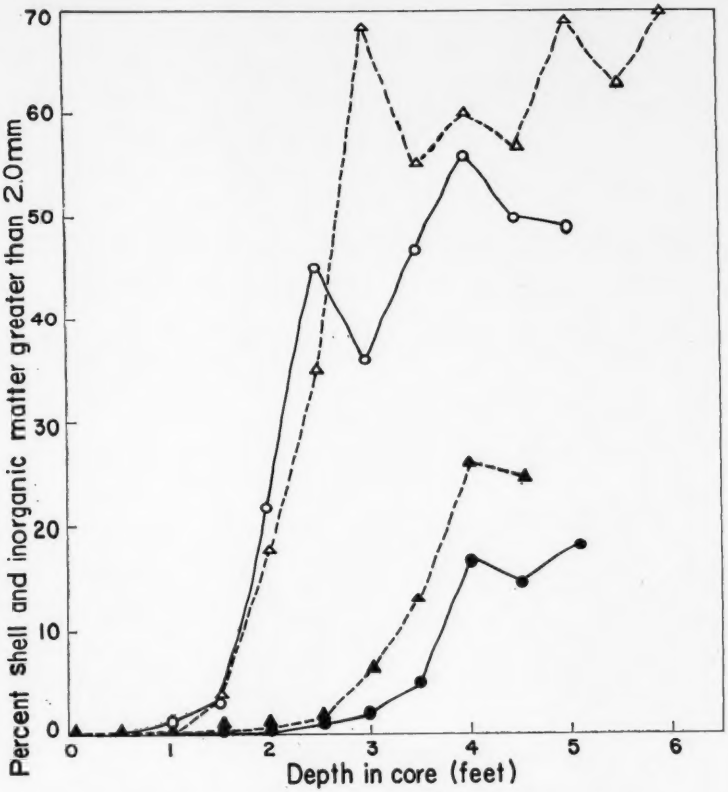

FIG. 3.—Relations of particles greater than 2.0 mm to depth in core.

zones in shelf sands are the rule and may be quite thick (fig. 4), they are virtually absent inside the Bay and, where present, quite thin.

APPLICATION OF THE HYPOTHESIS

The thickness of the traction zone in an underwater sediment depends primarily upon the current velocity and the density of the overlying fluid, as well as upon the specific gravity and size distribution of the sediment. The truth of this statement is generally accepted for the traction zone in river sediments. For Continental Shelf sediments an additional factor affects the traction zone thickness. This factor is the passing of swell over the sediments. A not unusual swell would have an amplitude of 2 feet and a length of 800 feet. In 70 feet of water it would produce horizontal current velocities of more than 0.3 foot per second. These currents are cyclic ranging from zero to a maximum first in one direction and then in the other with a period of about 12 seconds. The analysis of the hydraulic lift caused by a velocity gradient given by Ruby (1938) will clearly apply to

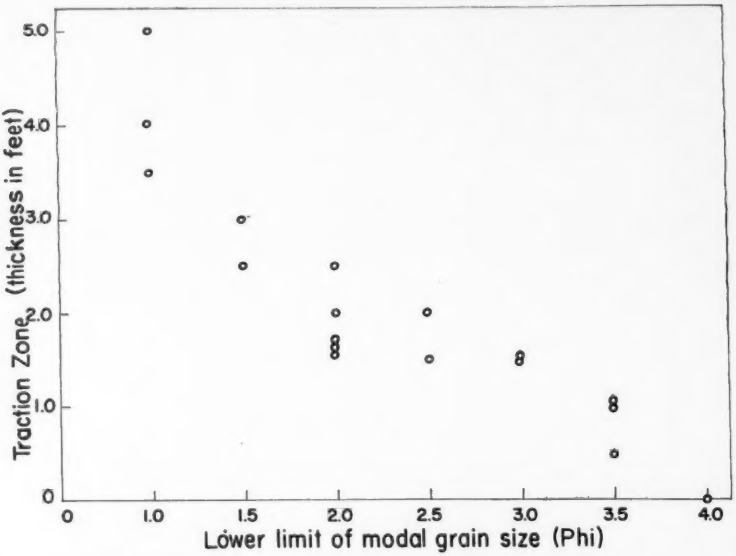

FIG. 4.—Relation between grain size and traction zone thickness.

these cyclic currents caused by swell. More important, however, in keeping the sand in motion to a considerable depth are the accelerations associated with the oscillation and the pressure gradients which cause flow into and out of the bottom sand. Discussions of these factors are to be found in O'Brien and Morison (1950) and Putnam (1949). Laboratory experiments show that agitation of water saturated sands produces vertical sorting. At some depth, however, motion caused by currents in the overlying water must stop and it is this level that we identify with the base of the traction zone.

Swell can easily account for the vertical sorting of the sediments, the accumulation zone, and the traction zone in offshore sandy sediments, and since there is very little swell inside the Chesapeake Bay it accounts as well for the absence of traction zones and accumulation zones inside the Bay everywhere except very close to the mouth.

For a given water depth and swell period the permeability of the sediment is the most important factor determining the traction zone thickness. In other words, the more freely the water can circulate in the sediment the greater will be its lifting effect. This accounts for the thinning of the traction zone as grain size and sorting decrease. Clay would be an extreme case since it is virtually impermeable. No traction zone has been observed in any of our clay cores.

The thickness of any particular traction zone is established by an adjustment to swell, water depth, and size distribution of the sediments. The profile thus obtained may not change in character upon the addition of sediments from above if the added sedimentary particles are large enough to sink to the bottom of the traction zone. The profile would retain its shape and simply move upward. The addition of fine sand would change the profile resulting first in a thickening

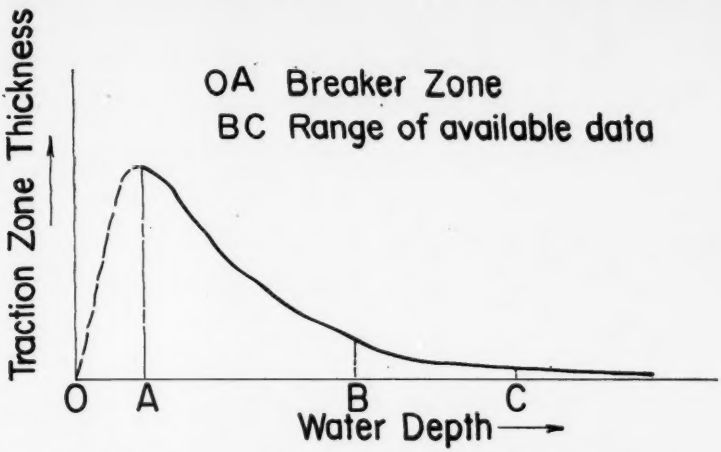

FIG. 5.—Schematic representation of the probable relation between traction zone thickness and water depth.

of the traction zone and finally in a complete upset of the original profile.

IMPLICATIONS OF THE HYPOTHESIS

During the lifting period in the traction zone the sediments are slightly loosened rendering them more susceptible to transport by horizontal currents. There is probably a lateral migration of the sediments in the traction zone in the current direction with a greater horizontal velocity toward the top.

Since the depth of the traction zone depends upon the oscillating velocities of the currents in the overlying water there should be a correlation between the thickness of the traction zone and the depth of the water. The effect of swell on the bottom should vary inversely with depth being greater at smaller depths. The relation is schematically indicated in figure 5. OA represents the breaker zone. A sample was investigated for correlation between the traction zone thickness and the reciprocal of the water depth. The range of available depths is about 50 feet but if rare cases are excluded is about 25 feet. The midpoint of the range is a depth of about 95 feet. Unfortunately this range is insufficient to permit the expected relation to emerge clearly from the neglected factors. The range of the data in relation to the expected function is indicated by the interval BC in figure 5. Still, a correlation of -0.30 with a standard error of estimate of ± 6.25 inches was found. It will be of interest to secure data from cores taken in water depths corresponding to the interval AB in figure 5 which can be expected to give a better correlation and a more precise idea of the form of the functional relation.

It is very unlikely that cross-bedding would be preserved in sediments subjected to the action of swell. If sea level were lowered, the shoreline would pass over the sediments in a seaward direction, resulting in a reworking by waves of the upper few feet. The wave action may produce cross-bedding in the upper few feet of the sediments. The swell hypothesis may account for the scarcity of cross-bedding in marine orthoquartzites.

The swell hypothesis may have an important bearing on the paleontology of Continental Shelf sands. Macro-fauna occurring in the zone of accumulation may

have been deposited at the same time as sand several feet higher in the sedimentary column. On the other hand, microfauna occurring in the traction zone may have their depositional equivalent several feet lower in the core.

It is interesting that the accumulation zone is sometimes composed of as much as 70 to 80 percent pebble sizes, and that they occur adjacent to a fairly low-lying coastal plain. This type of vertical sorting may well be expected on most Continental Shelf areas where grain size distribution, water depth, and swell activity permit.

ACKNOWLEDGMENTS

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REFERENCES

O'BRIEN, M. P. and MORISON, J. R. (1950) The forces exerted by waves on objects (revised): Univ. California, Dept. of Eng., Fluid Mechanics Lab., Wave Investigations Tech.Rept. ONR, U. S. Naval Contract N7onr-29528, Rept. HE-116-210, ser. 3, issue 310, Berkeley, California, Aug. 31, 1950.

PUTNAM, J. A. (1949) Loss of wave energy due to percolation in permeable sea bottom: Am. Geophys. Union Trans., vol. 30, pp. 349–356.

RUBEY, W. W. (1938) The force required to move particles on a stream bed: U. S. Geol. Survey Prof. Paper 189-E.

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DECEMBER, 1953

CYCLIC CALCAREOUS SEDIMENTATION AS AN INDEX OF CLIMATIC VARIATIONS IN THE PAST

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ABSTRACT

The sedimentary series of many regions show cyclic variations in calcareous content. Detailed studies made in the Helvetic zone of the Swiss Alps have led to the conclusion that such calcareous cycles are due chiefly to climatic variations. This hypothesis opens new prospects for both long distance correlation and palaeoclimatology.

Marine calcareous sediments are formed by the precipitation of calcium carbonate ($CaCO_3$)—mainly by organisms—and through its accumulation on the sea floor. During the process of deposition it is subject to the chemical influence of the sea water, and if the latter is undersaturated with $CaCO_3$ then the calcareous precipitate is partly or entirely redissolved. As a general rule, cold sea water is more or less undersaturated, and warm sea water is saturated or sometimes oversaturated. The formation of calcareous sediments is therefore greatly favored in warm, tropical, shallow seas, and hindered or even prevented in the cold water of higher latitudes and of greater depths.[1] Most present-day marine calcareous sediments are formed in low latitudes. Ancient marine limestone formations are also believed to have been deposited during warm climatic conditions, and many palaeogeographic and palaeoclimatic conclusions have already been drawn from their presence.

When a detailed study of limestones is made their interpretation becomes more difficult. Calcareous formations rarely consist entirely and uniformly of calcareous matter. Other sedimentary material is intermingled, most of it being sand and argillaceous matter of terrestrial origin which has been distributed over the sea floor by waves and currents. The proportion of calcareous and terrestrial matter can vary widely—laterally within a stratum, and vertically from bed to bed. Such changes of composition can be caused by variations either in supply of terrestrial matter, or in calcareous sedimentation (i.e. changing solubility of $CaCO_3$). In the second case, either a change in depth or a climatic change at the surface can be responsible for the change in composition.

In geologic literature most of these phenomena have hitherto been explained by changes in depth. In many instances, and especially for lateral changes of composition, changes in depth have certainly been of importance. Fossilized organic remains characteristic of different depth zones support such conclusions. There are however other examples of composition changes where the evidence is against this interpretation. The particular case considered here is cyclic calcareous sedimentation, which has occurred frequently in the epicontinental regions.

The following discussion of such cycles is based upon investigations in the Helvetic sedimentary series of the northern Swiss Alps. The presence of sedimentary cycles in the Helvetic zone was recognized by Buxtorf in 1910, and a detailed investigation made by Fichter in 1934. The principles that he estab-

[1] The solubility of calcium carbonate in sea water with its dependency on the CO_2 content, the temperature, salinity, etc., is a complicated problem and cannot be considered here in detail.

lished were followed by the present writer in 1937, and by some other students of the Helvetic sediments, too. Recently, the problem has been taken up, with modification, by Carozzi (1950, 1951) and again by the writer (1951). The detailed aspects of this subject were given in the last mentioned publication. This paper continues to stress the importance of the theory on cyclic sedimentation that resulted from that work.

A well-developed calcareous sedimentary cycle leads from shaly or marly beds at its base through alternating marl and limestone beds to a more or less massive limestone complex at the top. Then, alternating limestone and marl beds may form a transition to the marls or shales of the following cycle, but this transition is usually interrupted by a sharp break between limestone and marl. The break may or may not be followed by a bed of unusual composition, containing remarkable amounts of glauconite and/or phosphorite, pyrite, and large sand grains mixed in variable proportions. A number of these cycles are "incomplete," inasmuch as the sequence may start with the marl-limestone alternation, or even with the top limestones, or the upper members of the sequence may be missing. The main feature however of all the cycles is the alternating increase and decrease of the calcareous content of the rocks. Other accompanying changes of grain size, fossil content, etc. may be disregarded here. The thickness of the cycles ranges from a few meters to as much as 300 meters.

It was stated above that the successive changes in calcareous sedimentation at a given place can be caused by three factors. Their relative importance in the Helvetic cycles can be determined.

If the cyclic changes in $CaCO_3$ content depended on "dilution" caused by a varying supply of terrestrial matter, an increase of the "diluting" clastic matter would generally be expected towards its source, i.e. towards the old coast line. This hardly ever applies in the Helvetic zone; normally the contrary can be observed. Consequently, variability in terrestrial supply cannot have been the main cause for the cycles. There are, on the other hand, many signs of more or less intensive limestone solution visible throughout the Helvetic series, which show that changing conditions of calcareous sedimentation must have been of importance.

Repeated changes of depth, i.e. alternating uplift and subsidence of the earth's crust, have hitherto been believed to be the main reason for the $CaCO_3$ distribution in the Helvetic cycles. It was assumed that their shaly or marly basal part was deposited in comparatively deep and cold water, and the top limestones in comparatively shallow and warm water. In some large and "typical" cycles, this idea is supported by the presence of deep water fossils in the basal part and shallow water fossils at the top. The sharp break and the special bed at the "boundaries" between the cycles mentioned above would have to be caused "somehow" by slow or abrupt sinking. The conception of vertical movements was applied by Carozzi even to thin "subcycles" of very minor importance.

Such strong continuous oscillations of the earth's crust are unlikely, especially in the rather quiet epicontinental regions. Besides this, most of the smaller cycles (and all subcycles) contain shallow water fossils from bottom to top, though some of the cycles show remarkable changes in calcareous content. Therefore alternating up-and-down movements of the earth's crust cannot have been the main cause for them either, and they may never have happened at all. Only one movement of the earth's crust can be postulated: a slow gradual sinking of the sea floor. Many hundreds of meters of shallow water sediments have been deposited without leading to emergence, and on the whole, the subsidence and sedimentation have evidently kept pace with one another.

If it is now assumed that the cyclic changes of the calcareous content were due to climatic changes, i.e. to changes

of the average surface temperature of the sea, then, by combination with the slow subsidence of the sea floor, all the phenomena of the calcareous cycles can easily be explained. When the climate and the water became cooler, $CaCO_3$ solution would increase and the sedimentation would become slower. Subsidence and sedimentation were no longer in equilibrium, and the gradual deepening of the sea would result in increased limestone solution and consequent decrease of sedimentation. When, in turn, the climate and the water became warmer again, the solution of $CaCO_3$ would decrease and the calcareous sedimentation would consequently become more rapid, so that the subsidence of the sea floor could no longer compensate for the accumulation of sediments. The decreasing depth of the sea would lead to further increase of calcareous sedimentation. The sharp breaks and the special beds between the cycles, which both are characteristic of times of strong $CaCO_3$ solution, would represent the coldest phase of each cycle. The large "typical" cycles must have been produced by strong climatic variations, and the smaller and "incomplete" cycles as well as the little "subcycles" would correspond to minor climatic changes.

A comparison with the recent shelf sediments along the east coast of North America, similar in many respects to the Helvetic formations, provides an opportunity of assessing the amplitude of such climatic changes. There, in the Florida and Bahama region, entirely calcareous sediments are forming to-day. Towards the north, the calcareous content decreases until beyond Cape Hatteras only negligible amounts of $CaCO_3$ are deposited. The largest cycles of the Helvetic series might thus have corresponded to a wandering of climatic zones of about 5° of latitude, the smaller ones of about 2° or less. Climatic changes of this intensity are known in the Pleistocene times (glaciations), and these Pleistocene climatic periods may correspond also in their duration with the (smaller) cycles of the Helvetic series.

This new conception of cyclic calcareous sedimentation may prove to be satisfactory in many other regions, and the study of such cycles will be helpful for stratigraphic correlation as well as for the analysis of the palaeogeographic and palaeoclimatic history. Not only would it be possible to reconstruct many details of limited regions, as has been attempted invoking oscillation, since these movements can only apply to localized areas, but one might also succeed in correlating formations and climatic events over distances of continental size.

REFERENCES

BRÜCKNER, W. D. (1937) Stratigraphie des autochthonen Sedimentmantels und der Griesstockdecke im oberen Schaechental (Kanton Uri), eine Studie der nordhelvetischen Schichtfolge: Verh. der Naturf. Gesell. Basel, Band 48.

——— (1951) Lithologische Studien und zyklische Sedimentation in der helvetischen Zone der Schweizeralpen: Geol. Rundschau, Band 39.

BUXTORF, A. (1910) Erlaeuterungen zur geologischen Karte des Buergenstocks: Spez. Karte Nr. 27 der Schweizer Geol. Komm.

CAROZZI, A. (1950) Contribution à l'étude des rythmes de sédimentation: Archives des Sciences, vol. 3.

——— (1951) Rythmes de sédimentation dans le Crétacé helvétique: Geol. Rundschau, Band 39.

FICHTER, H. J. (1934) Geologie der Bauen-Brisen-Kette am Vierwaldstaettersee und die zyklische Gliederung der Kreide und des Malms der helvetischen Decken: Beitr. zur Geol. Karte der Schweiz, neue Folge, Band 69.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 23, NO. 4, PP. 238–259
FIGS. 1–11, PLATES 1, 2, DECEMBER, 1953

DIFFERENTIATION OF THE LOWER AND THE UPPER TILL ALONG THE NORTH SHORE OF LAKE ERIE

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ABSTRACT

Lower and upper tills from the area along the north shore of Lake Erie were studied by various field and laboratory methods in order to determine which of them would be the most suitable for later and more detailed investigations.

Where only differentiation of two tills is required the following methods were found to give the best results: determination of color and grain-size, petrographic analyses, particularly of the 0.5–1.0 mm grade, heavy mineral investigations and determination of carbonate content of the silt+clay grade.

Where provenance is the dominant consideration field studies of till fabric and till stones (alignment of stones, orientation of pentagonal pebbles, striage on boulder pavements), petrographic investigation of sand and pebble grades, heavy mineral investigations, particle size analyses, and determination of carbonate content, seem to be most suitable as illustrated in this paper.

Some preliminary conclusions are drawn in respect to provenance of the two tills and ice flow directions. The upper till has a higher percentage of local materials from the Lake Erie basin, such as Devonian shales and Pleistocene lacustrine deposits. This indicates an intensive erosion of the lake depression during the period of deposition of the upper till.

Differences in the pre-Cambrian components of the two tills suggest that the earlier ice flow, depositing the lower till, came from north-northeast, but the later one, depositing the upper till, was along the Lake Ontario and Lake Erie basins.

INTRODUCTION

A. P. Coleman, an expert on Pleistocene deposits in Canada, wrote the following statement in his last book "The Last Million Years" (1941, p. 69):

"The complicated history of the late glacial lakes and rivers of the Erie basin has been carefully worked out, . . .but the earlier glacial and interglacial record has received little study, though enough is known to suggest a strange succession of events. In many places around its shores the bed rock is buried under hundreds of feet of drift; including two or more till sheets and interglacial beds, but no systematic study has been made of them."

One of the most recent studies of the Pleistocene of Southern Ontario, by L. J. Chapman and D. F. Putnam (1951) also "leaves untouched the lower beds of the drift, the classification of which require a painstaking study of local stratigraphy" (quoted from pp. ix to x).

Members of the Department of Geology of the University of Western Ontario decided, early in 1950, that a start should be made on a systematic study of Pleistocene stratigraphy in Southern Ontario, particularly along Lake Erie. This area was chosen, as being the most suitable for correlation of Canadian Pleistocene deposits with those already studied and named in the United States.

Reconnaissance field trips, by A. Dreimanis along the north shore of Lake Erie and adjoining valleys in the area south and south-east of London, Ontario in 1948–1950, revealed at least three till sheets with stratified beds between them, exposed above the lake level.

The two upper beds looked very similar: they were silty and clayey, pale to yellowish brown, usually not rich in boulders and cobbles, but showing mostly

black shale among them. They were separated by varved silt or clay, with the maximal number of varves being only 15. The great similarity in the appearance of these till layers, the short time interval between their formation, and their stratigraphic position as the uppermost till layers lead to a common name for both of them—"*the upper till.*"

The deeper till sheet, exposed only in some places[1] was quite different: gray, sandy and gravelly, with abundance of boulders, mostly of limestone, but also showing some pre-Cambrian rock types which were not found in the upper till, such as tillite and jasper conglomerate. The black shale seldom was found in the deeper till bed. As this was the only exposed till layer below the upper till, it was called "*the lower till,*" though well logs indicated the existence of other and still deeper till beds.

More detailed field studies revealed a few till exposures having characteristics of both tills, somewhat intermixed, for instance; gray silty or clayey till or brown stony till. Therefore, it became necessary to gain a more thorough knowledge of both tills and to find suitable methods for their differentiation.

This task was assigned to K. S. Knox, a graduate student in the department during 1950 to 1952. He did heavy mineral studies, particle-size analyses, pebble counts, determination of their rounding, petrographic analyses of 0.6–1mm grade, and carbonate analyses, first using a limited number of samples (7), later increasing that number for some selected types of analyses up to 35 (see K. S. Knox, 1952).

As results of his thesis still showed some uncertainties, his investigations were continued by A. Dreimanis in 1952–53, and results of both studies are presented in this paper. Discussions in this paper are based upon analyses of 43 samples where at least 3 types of laboratory methods were applied, and an additional 32 samples with 1 to 2 types of analyses. Thus the total number of samples investigated has been increased to 75.

Most of this investigation was made possible by grants from the Research Council of Ontario though some materials from the Catfish Creek watershed were collected while A. Dreimanis was doing a ground-water survey for the Ontario Department of Planning and Development.

The field work and interpretation of the results of the field and laboratory studies was done principally by A. Dreimanis, the heavy mineral investigations were planned and supervised by G. H. Reavely and done principally by K. S. Knox, some by R. J. Cook, but other types of analyses were made by A. Dreimanis, K. S. Knox, R. B. Fraleigh, M. E. McClure, and R. Lee.

SCOPE OF INVESTIGATION

The following methods of investigation were chosen for comparison of the lower and upper till:

1. determination of color
2. studies of till fabric
3. particle-size analysis
4. pebble counts
5. determination of rounding of pebbles
6. petrographic analyses of 0.5–1mm grade
7. heavy mineral studies (percentage of heavy minerals in −20 to +100 mesh and their determination)
8. determination of the carbonate content

The authors realize that other methods of investigation could be applied and also a higher number of samples could be analyzed. It is hoped that this study will serve as only the beginning of a long-time project, with much more detailed and voluminous investigation to follow.

DISTRIBUTION OF TILL SAMPLES

The 43 samples, which were investigated by at least 3 methods, were taken from an 80-mile long strip along the north

[1] The principal exposures of the lower till are along Lake Erie 8–11 miles west of Port Stanley and in the Catfish Creek valley between Sparta and Aylmer.

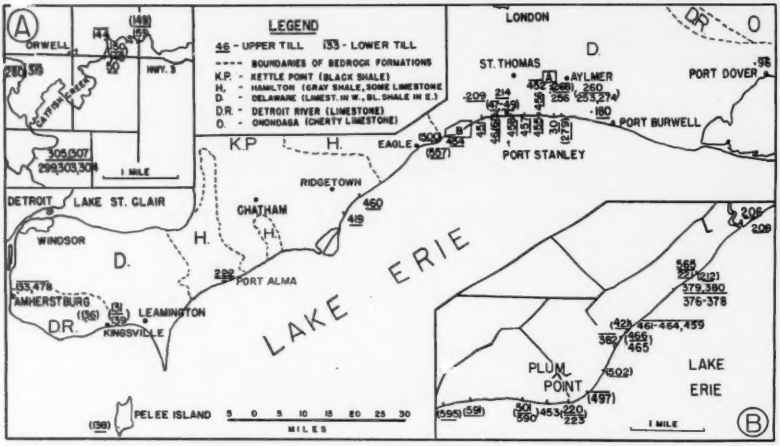

FIG. 1.—Bedrock boundaries and localities of till samples along the north shore of Lake Erie, Ontario. Less than three types of analyses are applied to those samples which have their numbers in parentheses, three or more to all other samples.

shore of Lake Erie, between Port Alma and Port Burwell (see fig. 1). Most of them derive from a smaller area, 30 miles long and up to 10 miles wide, between Eagle and Aylmer, because both tills are are well exposed there. A few additional samples, mostly from the lower till, were collected by A. Dreimanis and Mr. R. Packer from the Lake Erie shore area as far west as Amherstburg and as far east as Port Dover. These are approximately 160 miles apart in a WSW-ENE direction. Analyses of the upper till from the extreme east and west end of the area are not included in this paper because the upper till in the east, behind the Paris and Galt moraines, may be of Mankato age, and also because the stratigraphic position of the uppermost till at Amherstburg requires further investigation, as the samples collected show characteristics of both the lower and upper tills.

Three exposures of lower till were studied also in a vertical direction in order to find whether the composition and texture of it change from bottom to top: two of them were from the Lake Erie shore, 9 miles west of Port Stanley, and one was fr[illegible]ish Creek valley, 4.5 miles sou[illegible]Aylmer. At least 3 samples were taken from each exposure and at least five types of analyses or investigations were applied in their study.

AGE OF THE LOWER AND UPPER TILL

The lower and upper tills from the type area—southeast and southwest of London, resemble the two upper till beds of the Cleveland area, Ohio.[2] As White (1951, p. 976) assumes that the clay till of northeast Ohio is middle to late Cary and the earlier coarser drift is probably early Cary, the corresponding "upper" and "lower" tills of the north shore of Lake Erie are tentatively assumed to be of the same age: the upper till of late Cary and the lower of early Cary age.

COLOR

Over 100 tilll samples and exposures, including all the forementioned 75 samples, were examined, using a rock-color

[2] Both till sheets were compared in field trips with Dr. G. W. White in July, 1952 and found identical on both sides of Lake Erie.

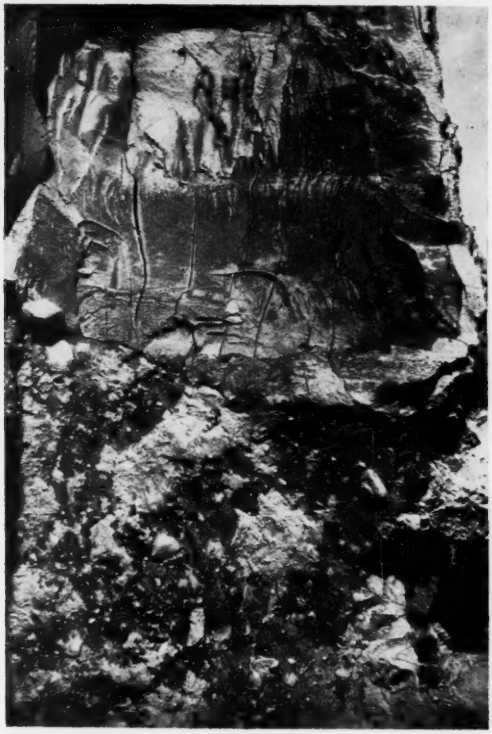

PLATE 1.—Upper clayey and lower stony till in an exposure one quarter mile west of Plum Point, Lake Erie north shore. Photo by Dreimanis.

chart, prepared by the Rock-color chart committee, (second printing, 1951, distributed by the Geological Society of America).

Some difficulties were encountered in applying the chart, because a wet till is darker than dry till and the color becomes yellowish if the till is oxidized.

Color of the *lower till* was found to be mostly light or medium olive gray (5Y6/1 or 5Y5/1), in some oxidized specimens tending to be pale or medium yellowish brown (10YR6/2 or 10YR5/2).

Color of the *upper till* is usually pale brown (5YR5/2) to pale yellowish brown (10YR6/2), becoming even more yellowish and lighter if oxidized. Some samples of the bottom portion of the upper till, for instance no. 565, or those from the western part of the area (e. g. no. 222) are of the same gray color as the lower till.

There is a definite difference in color between the upper and lower till in the central portion of the area studied. For a number of cases along the northwestern shore of Lake Erie, color can not be considered as a decisive criterion of differentiation.

TEXTURAL DIFFERENCES

The *lower till* is coarse in appearance in most places (see plate 1). It either carries interbedded layers or lenses of gravel at various locations or is itself very gravelly. Bouldery horizons may be seen at sever-

PLATE 2.—Shearing in the lower till one quarter mile northeast of Plum Point, Lake Erie north shore. Photo by Dreimanis.

al levels and shearing is evident in some places (see plate 2).

The *upper till* is finer, looks massive, and breaks in vertical cliffs with smooth partings (see plate 1). In some places it shows flow structures, indistinct bedding, and abundance of clay pebbles, particularly along the top or the bottom of the till beds. These features indicate that the ice probably was partly floating in the glacial lake at the beginning and at the end of deposition of the layers of upper till, and stratified lacustrine clay was interbedded with till. The upper till becomes coarser and similar to the lower till toward the west (e. g. near Ridgetown and Port Alma).

Alignment of stones, striae on boulder pavements, and axes of folds were measured in till exposures in order to ascertain the direction of ice flow.

Studies of *alignment of stones* were made principally by Richter's method (1932, p. 63), taking the compass direction of long axes of 50 to 100 pebbles. Pebbles ranged in size from one to five centimeters. Holmes' (1941) elaborate study of till fabric indicates that some types of pebbles prefer a parallel orientation while others a transverse position in respect to ice flow direction (p. 1345). As separate measurements of all the guide types, suggested by Holmes (p. 1345) lengthen the time of investigation, it was decided to pick out only a few from the abundant types of pebbles; those easy to distinguish and differing in their alignment (parallel or transverse). According to Holmes (pp. 1319–1322), a relatively high percentage of stones, with their intermediate axis dipping less then 70 degrees preferred a parallel alignment to the ice flow, while those, with the dip angle of the intermediate axis steeper than 75 degrees, preferred a transverse orientation.

Therefore, these two types of pebbles were counted separately in 35 till fabric analyses.[3] The results are shown in table 1, giving the percentage of stones, which

[3] These 35 and the further discussed 75 till fabric analyses dealing with pentagonal stones were made in various parts of Southern Ontario, and only those were selected for this discussion, where the ice flow direction was at least approximately known.

TABLE 1.—*Till fabric*

	Number of stones	Per cent	
		Parallel	Transverse
Composite group (intermediate axis dip 0–90°)	2198	36	19
Intermediate axis dip less than 70°	1495	38	14
Intermediate axis dip more than 75°	675	28	29

were aligned either parallel or transverse to the ice flow, within a range of ±15 degrees on either side of the parallel or transverse direction.[4] The results are similar to those of Holmes (see p. 1322), except for that group of stones which dip more than 75 degrees: an approximately equal number has either parallel or transverse alignment. The differences of alignment are quite distinct among the stones with their intermediate axes dipping less than 70 degrees: 38 per cent are parallel to the ice flow and 14 per cent are transverse to it. Therefore, *it is suggested that particular attention be paid to the abundant pebbles whose intermediate axes dip less than 70 degrees (or even less than 15 degrees—see Holmes, 1941, p, 1319), when it becomes necessary to differentiate a parallel maximum from a transverse maximum in till fabric diagrams.*

C. K. Wentworth's descriptions of the *pentagonal glacial cobbles*[5] (1936a, pp. 91–94 and 96; 1936b, p. 103) suggest that their pointed end is the push end.

Therefore orientation of the pentagonal pebbles was studied in 75 till fabric analyses, in order to determine whether they might be used in establishing whence the ice flowed. Only 612 pentagonal pebbles, aligned parallel to the ice flow (in limits of ±30 degrees), were found among the 5040 stones measured. Sixty-five per cent of them pointed toward that direction whence the ice came, 35 per cent in the opposite one. It is interesting to note that 80 per cent of the 75 analyses had more pebbles pointing against the ice flow than were pointing towards the ice flow, 12 per cent had equal numbers, and 6 per cent had more pebbles pointing with the ice movement. Therefore, it should be concluded that statistical studies of *the orientation of the pentagonal or flat-iron shaped stones may give a relatively good indication from where the ice came, but not in every instance.*

It has been noticed in several till fabric analyses that the *long axes* of most stones dip slightly against the ice flow. No statistical studies were made in this respect.

As alignment of stones reveal the ice flow for each particular location and horizon in till, local changes may be expected, and such were found in some cases by comparing results of investigations over short distances. Therefore, *a higher number of analyses, scattered through the area, may give a better general picture than a lesser number of very detailed investigations*, similar to those made by Holmes (1941) which require a longer time and therefore may permit study of only some few locations.

No bedrock is exposed in the area studied, but several *boulder pavements* or sheet-like *accumulations of cobbles* were found either at the base of, or within the lower till. These boulder pavements seem to be formed during the plastering of till, "by thrust from higher and faster moving debris" (C. D. Holmes, 1941, p, 1350) or by erosion of finer debris around them, leaving the firmly anchored stones as a pavement. These boulder pavements are relatively short, extending for 20 to 300 feet along exposures.

While measuring parallel striae on flat tops of boulders in pavements it was

[4] The range has been taken wider than in Holmes' study (10 degrees) because most of the maxima were wide.

[5] or the "flat iron" shape of O. D. Von Engeln (1930).

found that the direction of striae varied to a considerable extent from boulder to boulder in some cases. These variations may be explained by the dislocation of boulders during their striation or by the later compaction of till. In order to obtain more reliable data, *striae were measured on at least 10 boulders in each pavement.* If the 10 measurements did not give any definite maximum, the results were abandoned.

Crossing striae were found on several boulder pavements. The finest set was usually considered as the latest one. The older sets may either mean shifting of the boulders or a change in ice flow direction. Statistical evaluation may give the clue: if the older striae of all boulders do not have a definite parallel alignment, they indicate differential shifting and rolling of boulders during their deposition or striation. If the older set shows a definite parallel alignment in nearly all measured stones, it was taken to indicate another and older ice flow direction. Such instances are seldom, but they may suggest a period of dominant glacial erosion, with a change in ice flow.

Studies of *ice flow direction* by measuring long axes of pebbles, striae on boulder pavements and perpendicular to axes of folds revealed systematic changes of ice flow direction in each of the till beds (see Dreimanis, 1953b). Ice flow began from the lake at the beginning of deposition of each till bed (either the lower or the upper one), then turned more or less parallel to the lake and was again from the lake towards the end of the deposition of each till.

Therefore, ice flow direction could not be used for differentiation of the upper till from the lower till, but studies of changes of ice flow in each till bed may be very fruitful for deciphering the history of each ice advance and retreat.

PARTICLE SIZE ANALYSIS

Procedure

Approximately 1 to 2 pounds of till was taken, crushed slightly by a wooden roller, then coned and quartered. Pebbles larger than 1 inch were excluded. One hundred grams of sandy till or 50 grams of silty and clayey till were taken for the analysis, placed in a beaker with N/100 sodium oxalate and allowed to soak for one day, The first sixteen samples were boiled, as described in Krumbein and Pettijohn (1938, p. 73), in order to complete dispersion. All other samples were diluted to about 800 cc and dispersed by stirring for 30 minutes. An electrically driven loop-form stirrer operating at 750 r.p.m. was used throughout this work.

In order to find the necessary length of stirring time, M. McClure was assigned to study the effect of stirring by analyzing three till samples. Stirring was interrupted every 10 minutes, and 40 seconds and 1 hour hydrometer readings were taken in order to determine the percentage of clay, silt and sand. Results of these investigations are shown on figure 2. A relatively sharp increase in dispersion is demonstrated by the steep curves up to the 20 minute stirring period. Then they flatten out, though still showing some increase of dispersion up to the 40 minute period. Very slight changes existed between the 40, 50, and 60 minute stirring periods in samples 119 and 123, but flocculation was observed in sample 142[6] having the highest clay content. The flocculation may have been caused by increasing the number of collisions between fine clay particles, thus resulting in an increase in the rate of coagulation (see Krumbein and Pettijohn, 1938, p. 66).

The marked increase of the percentage of clay particles accompanied by a decrease in the amount of silt size while stirring from 30 to 40 minutes, may indicate disintegration of some of the silt grains.

The three experiments having to do with dispersion versus stirring time, indicate that at least 20 minutes, or better—*30 minutes of stirring are required for satisfactory dispersion of clayey and silty tills.*

An excessively long stirring may cause disintegration of some silt and sand

[6] Analysis of sample no. 142 was repeated, and the same results were obtained.

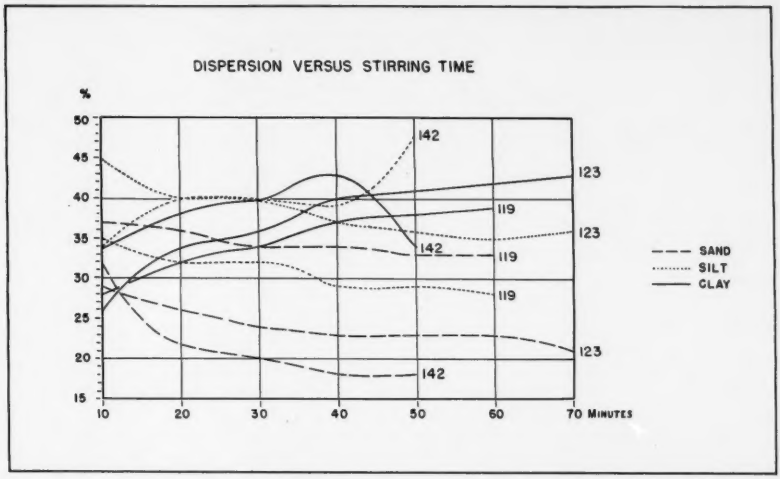

FIG. 2.—Dispersion versus stirring time in three till samples (nos. 119, 123, 142). Amount of each grain size in per cent is shown on the ordinate.

grains or have the opposite effect—namely flocculation of clay particles.

The *hydrometer method* (see Krumbein and Pettijohn, 1938, p. 174) was used for particle-size determination in finer grades and 40 second and 1 hour readings were taken to determine the amount of silt (0.05–0.005 mm) and clay (finer than 0.005 mm).

The material in the sedimentation cylinder after the hydrometer analysis was washed directly onto Tyler sieves and used for determination of percentage of sand grain sizes (not discussed in this paper) and also to obtain the 0.5—1 mm fraction for petrographic analysis.

Results

Thirty-eight samples of the upper till and 31 of the lower till were analyzed by this method, and the results are shown in figure 3.

Most samples of the *upper till* (36 of 38) are relatively clayey or silty and have less than 35 per cent sand and gravel. Two samples, 380 and 500, which show an exceptionally low amount of clay (7 and 10 per cent), cannot be considered as typical for the upper till. Sample 380 came from a small pebbly lens in the clayey and silty upper till and sample 500 from a very gravelly, though extensive, 1 to 2 foot layer of till with lenses of gravel. Both of them may represent a till reworked by water during its deposition. They were included in this study in order to show some exceptional varieties of the upper till.

The *lower till* may be characterized by a higher amount of sand and gravel than the upper till. Three samples (144, 319, and 497) are very close to the upper till in their grain size. As they represent till layers of a thickness up to 12 feet and are found both at Lake Erie and in the Catfish Creek Valley, they could not be considered as exceptional cases. Sample 274 was taken from a very gravelly, partly stratified layer of lower till, and, like samples 380 and 500 of the upper till, seem to represent till, reworked by water.

Figure 3 shows an obvious grouping of both tills in different parts of the diagram. *Therefore, grain-size analyses may be considered suitable for distinguishing the upper till from the lower till in most cases.* The slight overlapping in the central part of the diagram and the scattered

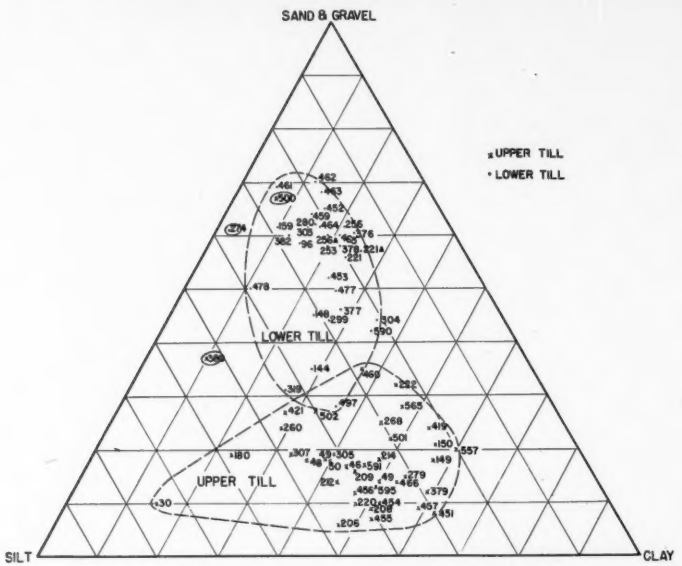

FIG. 3.—Mechanical composition of 69 till samples.

dots of reworked till indicate that results of this method may occasionally be confusing in which instances a cross-check by other methods is necessary.

Analyses of the three exposures of typical lower till with samples taken at several vertical intervals (see fig. 8) show variations in a single exposure up to 20 per cent. These results also indicate that the grain size of the till is not constant and varies not only laterally, as has been found by other workers (for instance Krumbein, 1933, Shepps, 1953, p. 43), but also vertically. Shepps (1953) has recently published results of 76 grain-size analyses of the Tazewell, early Cary and late Cary tills from northeastern Ohio. He has found that "in no case does one group contain samples which belong to another and hence there is no overlap in the mechanical compositions as expressed in percentages of sand, silt, and clay," admitting, however, "that the boundaries might overlap if more samples were run."

As Shepps also has analyzed tills from the Lake Erie lobe area, south of the lake, it is interesting to compare his results with those of the authors. It is obvious from comparison of the triangular diagrams (see Shepps' figure 2, and figure 3 of this paper), that mechanical analyses of the late Cary tills from both sides of the Lake reveal a correlation of one with the other. The lower till of the north shore of Lake Erie, however, corresponds to either the early Cary or the Tazewell tills of northeastern Ohio, if correlated on the basis of grain-size analyses. Therefore, further investigations are necessary as to the age of the lower till.

PEBBLE COUNTS

Seven samples, 4 from the upper till and 3 from the lower one, each of them weighing 20 to 150 pounds, were selected for this analysis by K. S. Knox (1952, pp. 28–31). The air-dried samples were broken into small lumps, placed on a 28 mesh sieve and soaked with a fine

spray of water, which washed away the fine clay and silt particles. The material remaining on the 28 mesh sieve was dried and resieved through the following Tyler sieves:

Mesh	*Openings in mm.*
—	13.33
—	9.423
3	6.680
4	4.699
16	0.991
28	0.589

The material between 16 and 28 mesh size was left for petrographic investigation, described on page 249.

Rock fragments, ranging from 4.699 mm to 8 cm in diameter, were used for pebble counts. Each of the grades (4.699–6.680 mm, 6.680–9.423 mm, 9.423–13.33 mm and 13.33–80 mm) was first analyzed separately in order to determine which of these ranges would be the most suitable for further studies, and to compare the results of analyses of different grades (see table 2).

TABLE 2.—*Pebble counts*

	Sample number	Grade mm.	No. of pebbles	Paleozoic rocks, per cent					Precambrian rocks, per cent			
				Ls.	Dol.	Shale	Chert	Ss.	Med.[7] grain acid	Med.[8] grain basic	Fine[9] grain acidic	Fine[10] grain basic
LOWER TILL	452	13.3–80	34	37	37	3	7	7	6	—	3	—
		9.4–13.3	19	26	21	—	10	16	11	11	—	5
		6.7– 9.4	52	33	29	—	13	6	14	—	—	6
		4.7– 6.7	200	37	29	1	9	6	8	4	3	2
		Total	305	35.5	29.9	+	9.5	6.9	8.9	3.6	2.0	3.3
	453	13.3–80	68	50	28	1	7	1	8	1	—	3
		9.4–13.3	53	45	26	2	4	6	6	10	2	—
		6.7– 9.4	136	46	21	5	7	6	13	2	—	—
		4.7– 6.7	321	46	32	4	4	5	8	1	—	1
		Total	578	45.0	28.6	4	5.0	5.0	9.0	2.4	+	1.0
	459	13.3–80	46	35	22	—	20	—	15	—	—	8
		9.4–13.3	53	33	30	3	12	5	6	6	—	4
		6.7– 9.4	145	40	28	2	8	5	9	2	1	6
		4.7– 6.7	448	44	25	1	7	2	13	2	—	7
		Total	692	41.6	25.6	1	8.4	2.3	12.3	2.2	+	6.4
UPPER TILL	451	13.3–80	15	33	13	40	—	—	13	—	—	—
		9.4–13.3	21	38	12	38	4	—	4	—	—	4
		6.7– 9.4	60	25	3	57	7	—	7	2	—	—
		4.7– 6.7	180	14	8	68	3	2	6	—	—	—
		Total	274	19.7	7.3	61.7	3.6	+	5.5	1.1	—	—
	454	13.3–80	4	50	50	—	—	—	—	—	—	—
		9.4–13.3	15	53	13	20	7	7	—	—	—	—
		6.7– 9.4	24	46	21	25	4	—	4	—	—	—
		4.7– 6.7	79	44	13	12	10	9	5	4	—	—
		Total	120	45.5	15.7	14.5	8.3	6.6	4.1	2.5	—	2.5
	458	13.3–80	33	51	—	36	—	9	—	3	—	—
		9.4–13.3	36	32	3	49	—	11	3	3	—	—
		6.7– 9.4	55	36	2	50	—	2	6	5	—	—
		4.7– 6.7	194	28	4	56	1	7	1	1	—	—
		Total	318	32.3	3.5	51.5	1	6.9	2.5	1.9	—	—
	460	13.3–80	17	29	18	29	12	—	6	6	—	—
		9.4–13.3	27	41	7	33	4	7	—	4	—	4
		6.7– 9.4	87	50	10	30	—	—	5	3	—	1
		4.7– 6.7	284	43	5	29	2	9	9	1	—	1
		Total	415	44.3	6.5	29.2	1.9	6.5	8.8	2.2	—	1.4

[7,8,9,10] See next page.

The following types of rocks were distinguished:

1. Pre-Cambrian rocks: medium-grained acidic,[7] medium-grained basic,[8] fine-grained acidic[9] and fine-grained basic.[10]
2. Carbonate rocks (Paleozoic): limestone and dolomite.
3. Shale (Devonian): black and light gray.
4. Chert (Paleozoic).
5. Sandstone (principally Devonian).

No significant trend in change of lithology from one grade to another was found in the seven samples analyzed. But, on comparing the percentage of carbonate clastics (limestone+dolomite) of the 6.7–9.4 mm grade with the 4.7–6.7 mm grade, an increase of these in the lower till, and a decrease of them in the upper till with diminishing grain size, was observed. As other rock types did not show any trend of change, and as the coarser grades had a small number of stones (4 to 53), Knox decided to count all four grades together. It is of interest to note that Krumbein (1933, p. 393) also used a wide range of pebbles ("all pebbles larger than 2 mm") for lithologic studies. The 4.7 mm to 13.3 mm grade is suggested for further studies, being the smallest one for easy megascopic examination and not requiring as much material as for a larger size.[11] Also this grain size may conveniently be used for comparing results with the work done outside of the area, as a similar grade of pebbles is used by several other workers. For example, Holmes (1952, p. 1000) has used 1/4 to 1/2 inch size (6.5–12 mm) and P. MacClintock and E. T. Apfel (personal communication) ¼ to ¾ inch (6.5–19 mm) grade in New York State, Davis (1951, p. 178) mostly 4–8 mm grade in Kansas.

[7] Medium-grained acidic rocks—granite, granite-gneiss, quartzite.

[8] Medium-grained basic rocks—gabbro, hornblende-, biotite-, or garnet-schist.

[9] Fine-grained acidic rocks—rhyolite and allied rocks.

[10] Fine-grained basic rocks—basalt, greenstone, etc.

[11] In order to obtain 200–400 pebbles of the 4.7–13.3 mm size from the upper till, it is necessary to wash up to 150 pounds of till.

The pebble counts (see table 2) indicate that the relative abundance of shale and dolomite may be utilized for differentiation of the two till horizons. The upper till contains 14–62 per cent shale, whereas the lower till contains not more than 4 per cent. The lower till contains 26–30 per cent dolomite—the upper till, 3–6 per cent. The ratio of Paleozoic to pre-Cambrian rock fragments is definitely higher in the upper till (7.3–14.7) than in the lower (3.6–6.4) (Knox, 1952, p. 39). It seems that all the four types of pre-Cambrian rocks, differentiated during the analyses, are more abundant in the lower till. No tillites and jasper conglomerates are found in the samples analyzed, though field evidences indicate them as being characteristic for the lower till.

The diagram (fig. 4), with a grouping of the following rock types: pre-Cambrian, Devonian shale and Paleozoic carbonate rocks (together with the calcareous or dolomitic sandstone and chert) shows a scattered distribution for the upper till. The samples of the lower till form a more compact group. The relatively high amount of carbonate rock fragments and chert, and the low percentage of shale, in sample 454 of the upper till brings it close to the lower. As sample 454 is from an exposure a short distance west of a buried end moraine of the lower till, this resemblance may be explained by admixture of lower till. The glacier, which deposited the upper one, overrode and partly eroded the end moraine, and included its material in the upper drift.

Knox concluded (1952, p. 45) that the pebble counts, . . ."although giving reasonably good results, require up to 150 pounds of till per sample. *The separation of the pebbles from this material and their subsequent determination is a long and arduous procedure.* It is the writer's opinion that for purposes of differentiation or correlation, the results obtained by this method do not justify the length of time required for an analysis. *When, however, it is desired to study the provenance of the material, this method is most suitable,* since the greater size of the pebbles enables an accurate determination."

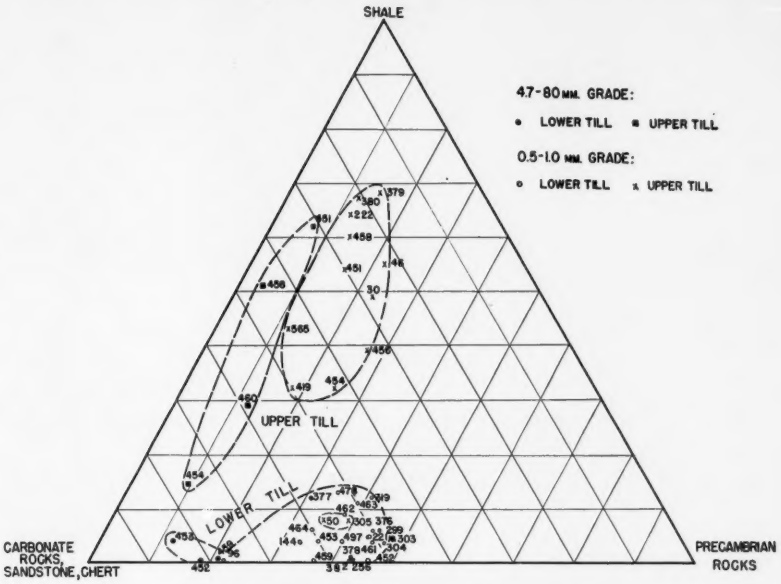

FIG. 4.—Petrographic composition of 34 till samples.

ROUNDING OF PEBBLES

Field observations indicated a better rounding of pebbles and stones in the lower till than in the upper one.

Therefore, rounding of pebbles was determined by Knox (1952, pp. 34–35, and 45) in the same samples which were used for pebble counts. Two size groups 4.7 to 6.7 mm and 6.7 to 80 mm were chosen for this purpose. The pebbles were divided into three classes: 1) angular and subangular, 2) subrounded and rounded and 3) well rounded (Pettijohn, 1949, p. 51–53). For simplicity in referring to them the above classes were called *angular, moderately rounded and well rounded*, which would approximately correspond to the three Wentworth groups: "(1) angular, rough, initial shapes due to the fracture characteristics of the rock and the disrupting process; (2) maturely facetted and striated cobbles; (3) rounded, water-worn shapes developed in super- and sub-glacial streams and in the glacial outwash channels" (Wentworth, 1936b, p. 103).

Results of this investigation are shown in a triangular diagram, as suggested by Wentworth (1936b, p. 104), on figure 5. It is seen that the 4.7–6.7 mm grade has a greater uniformity than the larger grade. *Although the pebbles contained in the lower till are generally more rounded, the results are not contrasting enough to be of a decisive value unless supplemented by some other methods.*

The lower degree of rounding of the pebbles in the upper till may partly be due to their lithology. Most of them are shale, which breaks easily during glacial transport forming angular fragments.

PETROGRAPHIC ANALYSES OF 0.5–1 mm GRADE

Petrographic analyses of the 0.5–1 mm grade[12] washed out of till was used for this investigation, and 34 samples were studied (21 from the lower till and 13 from the upper till).

As the procedure adopted was described

[12] A 0.6 mm sieve was used instead of a 0.5 mm one until the correct sieve was received.

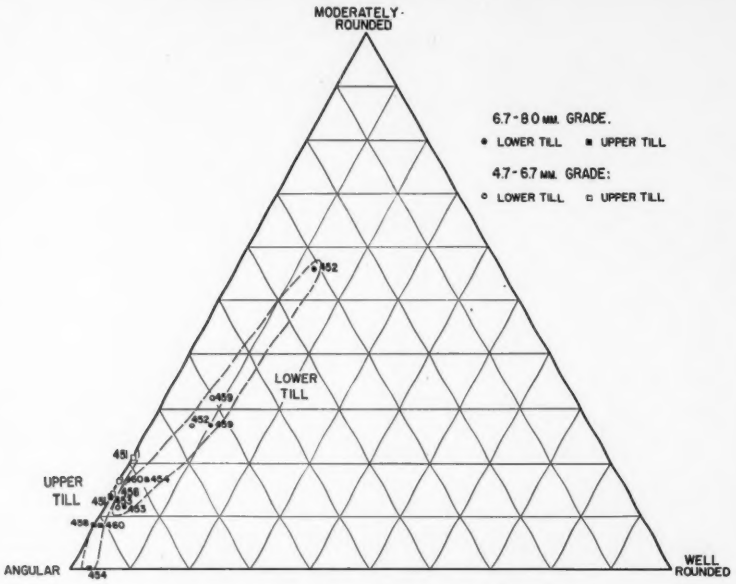

FIG. 5.—Rounding of pebbles in 7 till samples.

in a paper out of print (Dreimanis, 1947) and the great abundance of shale in the upper till has necessitated some modifications, the method is outlined here (see also; Dreimanis, 1953a).

Procedure

Two hundred grams to one kilogram of till were washed through a series of two Tyler standard sieves arranged in order of decreasing size of opening. The following sizes were used because they gave closest grades to the above limits (0.5 and 1.0 mm):

16 mesh sieve with openings of 0.991 mm,

32 mesh sieve with openings of 0.459 mm.

Material plus 32 mesh and minus 16 mesh was coned, quartered and sampled by the nine-point method. This sample was again quartered and as much of the material taken as would cover the tip of a spatula (about 350 to 500 grains), without counting. They were spread on black paper. All grains which looked like *sandstone* were first removed, using tweezers and a hand lens. Each of them was immersed in a drop of 20 per cent hydrochloric acid on a glass plate; all sandstone grains left some quartz particles as a residue, these being identified by the grinding sound produced when rubbed with tweezers against the glass plate. A granular limestone or dolomite dissolved in the 20 per cent hydrochloric acid without leaving such residue. Whether the particular grain was dolomite or limestone was determined by the degree of effervescence shown. Each of these grains was later added to its respective group.

After separation of the sandstone, the remaining grains were put into a Petri-dish containing 5 per cent acetic acid. *Limestone* grains showing effervescence were removed and counted. Since the calcareous shales also evolved bubbles of carbon dioxide, all grains effervescing were gently pressed with tweezers—*shales* disintegrating under the slight

pressure. These were counted separately. The non-calcareous gray shales also disintegrated under a slight pressure. They too were separated at this time and counted along with the calcareous shales. After limestones and shales had been so removed, the acetic acid was discarded, the remaining grains were washed, and a 10 per cent hydrochloric acid solution was poured over them. The *dolomites*, showing a similar reaction to that of the limestones in acetic acid, were also picked out and counted. Some black dolomitic shales were found at this time by the same procedure as for the other shales in acetic acid. They were added to the other shales.

Thereafter the acid was decanted and the grains were washed and dried on filter paper. All *mafic minerals and rock fragments* were removed and counted as a separate group. The same was done with *chert*. The remaining grains consisted of *feldspars* and *quartz*. These were separated using hydrofluoric acid in the following manner. The grains were placed in a lead crucible, a few drops of the acid were poured over them and allowed to remain for three minutes, the whole being kept in a fume cabinet. The acid was decanted, the grains were washed with water, dried in an air oven, and spread on black paper. Since only the feldspars became covered with a white deposit of fluorides they were thus easily separated from the clear quartz grains.

The results of analyses and a comparison with the possible source areas showed that the various types of rock fragments and minerals could be grouped in three classes according to their origin:

1) *pre-Cambrian* rock fragments and minerals: feldspar, dark minerals and rock fragments and most of the quartz;

2) fragments of *Paleozoic carbonate* rocks (limestone and dolomite), along with chert found in these rocks, together with Oriskany sandstone (a thin bed between the Onondaga and Bertie-Akron limestone and dolomite). The principal bedrock exposures from which these rock fragments derive are between the area studied and Lake Ontario;

3) gray and black *Devonian shale*[13] (the Delaware, Hamilton and Kettle Point formations), forming the principal bedrock in the area under consideration.

Thus, a triangular diagram is readily applicable as an aid to evaluation of results (fig. 4). It is to be noted also that the analytical procedure may be simplified in future investigations. The following modification is suggested.

The analyzed portion (350–500 grains) is first counted and then placed in 20 per cent hydrochloric acid. All limestone and dolomite grains will dissolve in from one half to one hour. Though sandstone grains and calcareous shales will lose their carbonates, they will not disintegrate, unless compressed by tweezers. While testing them with tweezers it is easy to distinguish shale from sandstone. Both of them are counted while all grains are still in the acid.

Thereafter, the acid is decanted, the remaining grains are washed, dried, and the chert is removed. The rest consists of quartz, feldspar, dark minerals and rock fragments, which are counted together as pre-Cambrian.

The amount of limestone and dolomite is found by subtracting all the counted grains from the total.

This simplified procedure cuts down the time required for an analysis to less than an hour, when a series of samples is analyzed.

Results

It is seen that the results of petrographic analyses of the 0.5 to 1 mm grade are relatively constant in either till along Lake Erie, particularly in the lower till (see figs. 4 and 8). This provides distinction of the upper till from the lower.[14] The lower till differs from the upper particularly in its very low content of shale, the correspondingly higher percentage of carbonate and pre-Cambrian rocks and

[13] Some Silurian shale and even the reddish brown Queenston shale may be admixed, but in a small amount due to a rapid diminution of these soft fragments by crushing during the glacial transport.

[14] With some exceptions, which will be mentioned farther down.

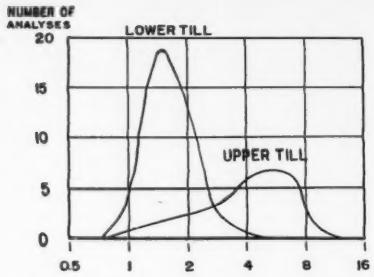

FIG. 6.—Ratio of Paleozoic to pre-Cambrian rock fragments and minerals in the 0.5–1.0 mm grade of tills along the north shore of Lake Erie.

by its lower ratio of Paleozoics to pre-Cambrian rock fragments and minerals (see also fig. 6). As these differences appear clearer from the analyses of the finest grade than from the results of pebble counts and this method requires less material and less time, Knox (1952, p. 45) preferred it to the latter, and with this the writers concur.

The two samples of upper till (nos. 50 and 305, fig. 4) which were taken at a distance of six to eight miles north of Lake Erie have the same composition as the lower till. *Therefore, it appears that the use of the foregoing petrographic method for clear differentiation of the upper from the lower till is valid only for a narrow strip along Lake Erie.* It may serve for further differentiation of various types of the upper till and for provenance studies of till material.

HEAVY MINERAL STUDIES

The +100 mesh and −20 mesh grade (0.147 mm to 0.833 mm) was used for this investigation, as the same fraction has been applied for heavy mineral studies of glacial deposits in other parts of southwestern Ontario.

Though statistical studies of heavy minerals are usually made on a finer grade (see Leinz, 1933, Krumbein, 1933, Gravenor, 1949, Russell, 1936, a.o.), Reavely decided to investigate this relatively coarser grain size because of the following considerations. Generally increasing specific gravity is accompanied by increasing fineness of the heavy minerals. This means that for any size range the lower size limits of this range will favor a greater relative quantity of heavy separates. The relative amount of any mineral or group of minerals is dependent also upon its size in the source rocks and it is generally the excessively heavy accessory minerals which are finer. Thus very fine heavy detritals might tend to favor source rocks with relatively more heavy detritals. It was felt that a wider range of particle size in a slightly larger grain size would have less chance of favoring a special source, in particular of favoring a sedimentary source over a crystalline one.

Procedure

The usual procedure was applied in preparation of the heavy mineral concentrates (see Krumbein and Pettijohn, 1938, p. 335): dissolving all carbonates in 1 normal hydrochloric acid and then using bromoform (sp.gr. 2.89) as the separating liquid.

The basic procedure used for the identification of the heavy minerals was the immersion method (Dana, 1950, pp. 236–239). After this, other optical properties were studied and where necessary thin sections of mounted grains were prepared.

The following minerals were found in the heavy mineral content of the tills: magnetite, ilmenite, hematite, limonite, hornblende, garnet, zoisite, monoclinic pyroxene, hypersthene, epidote, tremolite, actinolite, micas, marcasite, pyrite, chalcopyrite, zircon and rock fragments with serpentine.

Once the minerals were identified it was possible to recognize them again under reflected light using a binocular microscope.

For counting purposes a piece of light cardboard was ruled off with lines one-fourth inch apart. The heavy minerals were spread over this area, the magnetic fraction (magnetite and ilmenite) was separated, using a small magnet covered with a piece of light paper, but other

minerals were determined under the microscope using the spaced lines as traverses, and at least 300 grains were counted from each sample (for a detailed description of the procedure, the probable errors, and description of the minerals, see R. J. B. Cook's thesis (1952, pp. 9–23).

Results

Thirty-three till samples (15 from the lower till and 18 from the upper) were analyzed by this method and most of the results may be found in K. S. Knox' thesis (1952, pp. 11 and 12).

The only heavy mineral showing a significant percentage difference between the two tills was garnet. The upper till usually contained a greater amount of purple garnet than red garnet, but the lower till contained a higher percentage of red garnet. *Therefore, differentiation of lower from upper till was found to be possible by considering the purple to red garnet ratio. In a few instances some overlapping occurred.* The lower till shows more uniform results (ratio 0.5–1.0), while the samples of the upper till are scattered over a wide range (0.6 to 3.0) see figure 7.

Knox (1952, pp. 10–17) used a similar ratio of purple to light red garnets and found it diagnostic for either till. As it was difficult in some cases to distinguish light red from dark red garnet and most samples with a greater abundance of light red garnet had also more dark red garnets, the writers decided to put both red garnets together for the above ratio. Though the first samples analyzed indicated no overlapping in the garnet ratios of the lower and upper tills, an increase of the number of analyses brought out some (see fig. 7). Therefore, this method could not be considered as diagnostic for differentiation of upper from lower till, as was assumed by Knox (1952, p. 58).

Some other observations from the results of heavy mineral analyses should be mentioned because they may be of help in future studies concerned with their provenance. The lower till contained slightly more hornblende and epidote

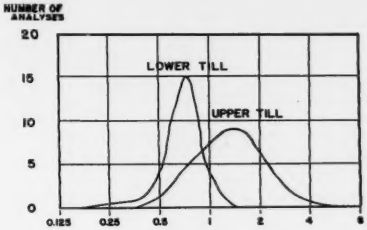

FIG. 7.—Ratio of purple to red garnet in the 0.15 to 0.83 mm grade of tills along the north shore of Lake Erie.

and less tremolite and actinolite than the upper till. The amount of sulphides varied a great deal from sample to sample, being dependent on the underlying bedrock type (Knox, 1952, p. 16).

The amount of sulphides increased up to 38 per cent in some samples from the area where the Kettle Point formation occurs as bed rock. As sulphides are predominantly of local origin, while other heavy minerals derive from the distant pre-Cambrian rocks, it is sometimes necessary to exclude sulphides, when only pre-Cambrian minerals are discussed.

Thus, if the relative amount of pre-Cambrian material is computed from the percentage of heavy minerals (as was done, for instance, by Gravenor, 1949), the sulphides should be excluded from the calculation, if they exceeded 2 per cent.[15]

The percentage of heavy minerals (excluding the sulphides which exceed 2 per cent) ranges from 0.2 to 4.0 in the −20+100 mesh grade.

As till samples were taken from different depths in both tills, it was tried to group them accordingly, because till fabric studies (see p. 244) disclosed that the basal portion of either till bed has been deposited by a different ice flow than the middle part.

Figures 8 and 9 show a definite group-

[15] Two per cent has been the maximal value of sulphides in 13 analyses of tills from the pre-Cambrian area or just south of it (Cook, 1952, p. 30).

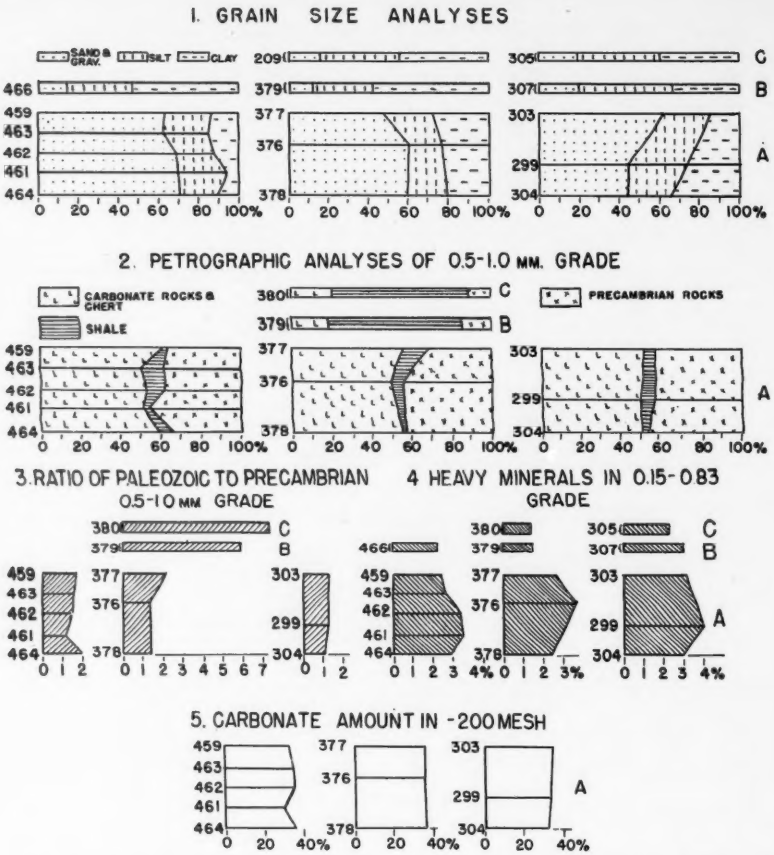

FIG. 8.—Five types of analyses in three profile sections (see fig. 1 for their locations). A—lower till, B—first bed of the upper till, C—second, uppermost bed of the upper till. Though sample no. 209 was not taken from the profile section nos. 376–380, its results of grain-size analysis are shown as being characteristic of the uppermost till of that area. Vertical distance between the highest (nos. 459, 377, 303) and lowest samples (nos. 464, 378, 304) in the lower till is approximately 30 feet.

ing of the percentage of heavy minerals of pre-Cambrian origin at various depths of the lower till and the upper till. These differences, combined with the results of till fabric studies, have led to the conclusion (Dreimanis, 1953b), that ice-flows from the Lake Erie basin carrying a higher amount of local material (both Pleistocene and bedrock), existed at least during the initial stages of deposition of the lower and upper till and probably also during the end stage of plastering of the lower till. The middle portion of the lower till, deposited by an E-W or NE-SW ice flow, shows the highest percentage of heavy minerals, and therefore indicates a lesser admixture of local material. Though these conclusions are

based upon a relatively small number of analyses, they indicate that *determination of the percentage of heavy minerals may be used for a detailed study of the glacial history of the Lake Erie area if samples are taken from various depths of each till bed.*

CARBONATE CONTENT

The carbonate content of 36 samples, 17 from the upper and 19 from the lower till, was determined by means of the Chittick gasometric apparatus, using 6N hydrochloric acid and analyzing 1.7 grams of material in each case.

First the −20 mesh grade (with sieve openings of 0.84 mm) was used for the carbonate analysis. This insured against abnormal variations in CO_2 content due to the presence of pebbles of one composition in the material being treated.

While experimenting with pure calcite and dolomite, it was observed that all the calcite was decomposed during that interval of time when the 20 ml of acid was run into the decomposition flask. Eight to ten per cent of the dolomite was decomposed during the interval. This difference in speed of reaction of hydrochloric acid with carbonates made it possible to determine the approximate ratio of calcite to dolomite in the sample. This is necessary when calculating the weight of carbonate from the amount of carbon dioxide. The average ratio of calcite to dolomite was found to be 2:1.

As no difference was found between the upper and lower till[16] after analyzing 23 samples in spite of the obvious difference in the carbonate content of pebbles (see fig. 4), Knox (1952, p. 54) "decided to reanalyze six samples of the upper till and six of the lower, using the material passing through a 200 mesh sieve; that is the silt and clay" (plus some very fine sand). This was done in order to compare more uniform material. Cumulative curves of grain size analyses of tills (Knox, 1952, p. 24) showed that the lower till contained approximately 60 per cent of sand, the upper one approximately 20 per cent. An analysis of glacial clay from eastern Canada (Terzaghi and Peck, 1948, p. 20) indicated that quartz tends to congregate in a coarser grain size than does calcite. Consequently, Knox felt that it was unwise to use such grade (−20 mesh) for comparative purposes, since it was built up of unequal constituents in either till. The −200 mesh grade 1) did not possess the sand grains (except of very fine sand) and 2) it was built up of relatively equal proportions of silt and clay in either till, and therefore was preferable. The percentages of carbonates obtained for the six upper till samples were approximately the same as in the previous analyses. This was to be expected since the upper till contains little sand. However, with one exception, the percentage of carbonate for the lower till samples was considerably greater than the values obtained previously (Knox, 1952, p. 54). The increase was from 1.6 to 19.5 per cent.

The number of parallel analyses of −20 mesh and −200 mesh grades of the same till samples was increased from 12 to 25 by Dreimanis. Results of these as well as other single −20 mesh or −200 mesh analyses are shown in figure 10. An increase in the carbonate content is

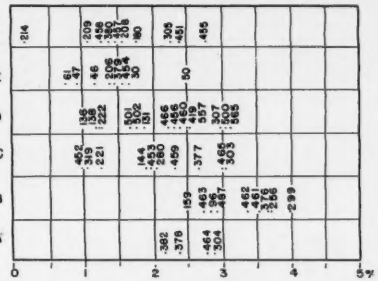

FIG. 9.—Percentage of heavy minerals in the 0.15–0.83 mm grade along the north shore of Lake Erie. A—base of the lower till, B—middle portion of the lower till, C—top of the lower till, D—base of the first bed of the upper till, E—middle portion of the first bed of the upper till, F—second, uppermost bed of the upper till. Figures at dots are file numbers of till samples.

[16] 20.4–32.4 per cent in the upper till, 24.8–32.4 per cent in the lower till.

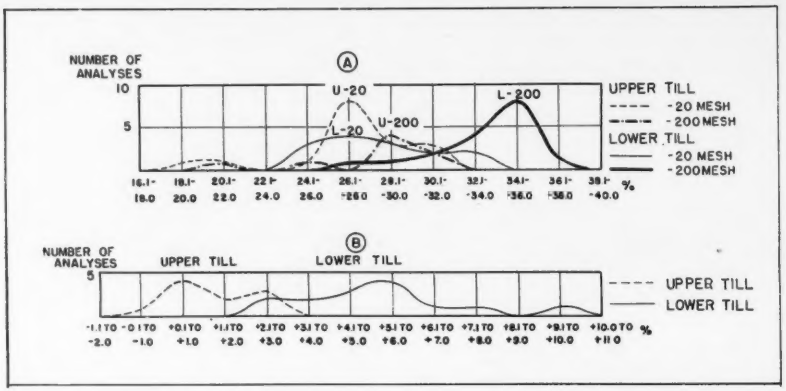

FIG. 10.—A—carbonate amount in tills along the north shore of Lake Erie. B—change (increase or decrease) in carbonate amount between results of analyses of the −20 mesh and the −200 mesh grades of tills.

noticeable in both tills (with one exception, no. 209, upper till), but, as a rule, it is more evident in the lower till. This difference in carbonate amount between the −20 mesh and −200 mesh grades may be used for distinguishing the upper till from the lower in many cases. *Though the −200 mesh grade of the lower till has a relatively higher percentage of carbonates (28.0–38.5 per cent, as compared with 21.7–32.0 per cent in the upper till), the results still overlap.* Therefore, *the carbonate content could not be consided decisive for differentiation of the upper from the lower till.* No definite changes in carbonate content were found in samples from different depths in the lower till (see fig. 8).

As the limit of −200 mesh was chosen by Knox arbitrarily, Dreimanis decided to investigate the distribution of carbonates in some till samples over various grades. Two samples of typical upper (no. 279) and lower (no. 256) tills were taken from the east end of the area studied and a sample of an intermediate type (no. 222, an upper till with admixture from the lower one) from an exposure approximately 75 miles southwest of the previous area. Two hundred grams of each sample was treated as follows: soaking in 0.01N sodium oxalate solution, stirring for 40 minutes, sieving through 16, 32, 60, 150 and 250 mesh sieves and separating silt (+some fine sand) from clay by decantation. The carbonate of each grain-size (except of the coarse +16 mesh) was determined separately, and the results were plotted on semi-logarithmic paper, with the percentage of carbonates marked at the middle of each particular grade. The connecting curves turned out to be of a similar pattern in all three cases (see fig. 11).

The trend of these curves explains clearly why the −20 mesh carbonate determinations were at variance with the −200 mesh grade, the principal difference being between fine and very fine sand with a low carbonate content (excluded in the −200 grade) and the high-carbonate silt. Even the −200 mesh grade is not homogeneous, and its carbonate content changes, though with a general high in the silt size.

Therefore, if grades with uniform carbonate content are desired for comparison of such in tills, it would be better to choose the silt grade alone as it has a high amount of carbonates in all three

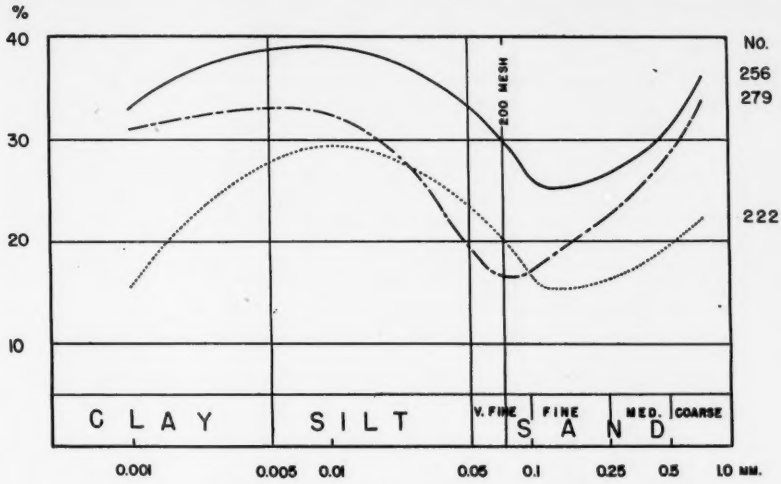

FIG. 11.—Carbonate amount in various grades of three till samples.

samples examined. However, separation of silt grade requires several hours time.

Another important factor should be considered in evaluating the results of carbonate analyses. This is the composition of the local bedrock. Knox found from 14 analyses of the upper till that the average carbonate content of samples from the area underlain by the Delaware limestone and shale is higher (28.5 per cent) than those from the area underlain by the Hamilton and Kettle Point formations (22.5 per cent) which are composed principally of shale.

Therefore, determination of the carbonate content may be applied to studies of *provenance of till*, but "before differentiation of the tills by their carbonate content is attempted the area influenced by the underlying bedrock must be delineated" (Knox, 1952, p. 56).

SUMMARY

The "upper" (probably late Cary) and the "lower" (probably early Cary) till from the area along the north shore of Lake Erie have been studied by various methods to determine which of them would be most suitable for later and more detailed investigations.

Results of all the methods applied showed some overlapping, and therefore none of them could be considered decisive in the determination of any unknown sample. Therefore, application of several (at least three) types of investigation are suggested if the stratigraphic situation of a sample is not certain.

The following methods gave the most distinct differences between the upper and the lower till:

1) Determination of color of unweathered till—the lower one is olive gray, the upper is pale brown, except in the western part of the area.

2) Particle size analysis—the lower till is more sandy than the upper one in most cases.

3) Petrographic analyses—the lower till is richer in Paleozoic carbonates and pre-Cambrian rocks than the upper one, and the upper till shows abundance of shale fragments along Lake Erie. This difference does not exist farther north of the lake. The lower till is richer in red garnets than the upper one. The most

rapid methods of petrographic investigation are the analyses of 0.5–1.0 mm grade and heavy mineral studies. Pebble counts require too much time.

4) Determination of carbonate content—relatively higher in the lower till, particularly if merely the −200 mesh grades are compared.

If provenance of tills and changes of ice flow direction are the principal aim of studies, the following laboratory methods may serve the best:

1) Petrographic analyses of the 0.5–1.0 mm grade and pebble counts, principally for local materials, and heavy mineral analyses for distant sources.

2) Determination of carbonate content, supplementing the petrographic analyses.

3) Particle size analysis, giving particularly some clue on admixture of older stratified materials in tills.

For field studies, observations of till fabric and striae on boulder pavements are essential, and every sample taken for laboratory investigations should come from horizons where ice flow direction has been determined in the field. Alignment of those pebbles, which have their intermediate axes dipping at less than 70 degrees, as well as measurements of striae on boulder pavements, has been found appropriate for determination of ice flow direction. Statistical evaluation of the directions in which the pentagonal pebbles point may indicate the direction in which the ice moved (the majority point in that direction from which the ice came).

PRELIMINARY CONCLUSIONS AS TO THE PROVENANCE OF THE UPPER AND LOWER TILL AND ICE FLOW DIRECTIONS

Though the somewhat small area covered by this study requires expanding before drawing general conclusions, the authors feel that some preliminary conclusions may be drawn.

The upper till reflects more the material of the Erie lake basin (both the shaly bedrock and the Pleistocene lacustrine deposits) than does the lower till. Petrographic analyses point to a lesser amount of pre-Cambrian rock fragments in the upper till. Therefore, the conclusion that the upper till is composed of more local material than the lower till is justified.

Studies of ice flow directions and petrographic investigations indicate that the ice sheets advanced from the lake depression at the beginning of deposition of either the lower or upper till (see Dreimanis, 1953b, for more details). They suggest even the existence of a local center of glacial outflow at the beginning of each advance. Later, during the main period of deposition of till, the ice flow was principally from the east; during the deposition of the lower till it was even from the northeast for some time. This flow from the northeast, across the Niagara peninsula with its calcareous Paleozoic rocks, may account for the high percentage of carbonate materials in the lower till.

The differences in petrographic character of the pre-Cambrian rock fragments between the lower and upper till and their comparison with till analyses from the southern border of the Canadian shield[17] suggest the following:

1. The ice flow which deposited the upper till along Lake Erie crossed the southeastern portion of the Grenville subprovince in Ontario.

2. The earlier ice flow which deposited the lower till has come across that part of the Grenville which lies west of the previous area (i.e., northeast of Lake Simcoe); some rocks (e.g., tillites) have come from the area north of the Grenville subprovince.

All the evidence discussed herein indicate that the *principal ice flow*[18] *was from north-northeast, across the mainland of Southern Ontario, during the deposition of the lower till. It was more from east-northeast, along the Lake Ontario and Erie*

[17] See Cook, 1952, p. 29.

[18] Except for the beginning and end of each ice advance when local centers of outflow may have existed in the lake basins.

basins during the deposition of the upper till.

The studies along the north shore of Lake Erie are not sufficient to decide whether this later ice flow came from the Labradorian center of glaciation or merely from a local center of glacial outflow in the Lake Ontario region, which was suggested by Holmes (1952) at least for some part of the Wisconsin age.

REFERENCES

CALEY, J. F. (1943) Palaeozoic geology of the London area, Ontario: Geol. Survey Canada Mem. 237, 171 pp.

——— (1945) Palaeozoic geology of the Windsor-Sarnia area, Ontario: Geol. Survey Canada Mem. 240, 227 pp.

CHAPMAN, L. J. and PUTNAM, D. F. (1951) The physiography of southern Ontario: Ontario Research Foundation, 284 pp.

COLEMAN, A. P. (1941) The last million years: The University of Toronto Press, Toronto, 216 pp.

COOK, R. J. B. (1952) Heavy detritals and glacial stratigraphy in southern Ontario: unpublished master's thesis, University of Western Ontario, 82 pp. Abstract published in Canada Mining Journal, 1953, vol. 74, p. 100.

DANA, E. S. (1950) A textbook of mineralogy; 4th ed., revised by W. E. Ford: John Wiley & Sons, New York, 851 pp.

DAVIS, S. N. (1951) Studies of Pleistocene gravel lithologies in northeastern Kansas: Kansas Geol. Survey Bull. 90, pt. 7, pp. 173–192.

DREIMANIS, A. (1947) An improved petrological method (1939) for the investigation of boulder clays: Contr. Baltic Univ. 46, 8 pp.

——— (1951) Ground water: Catfish Creek Cons. Rept., Ontario Dept. of Planning and Devel., pp. 1–79.

——— (1953a) Nature lithologique des dépots glaciaires près du Lac Érié: Cahiers Géol. de Thoiry, xvi–xvii, pp. 147–151.

——— (1953b) Evidences of lowland centres of glaciation and cirques in southern Ontario: manuscript.

GRAVENOR, C. (1951) Bedrock source of tills in southwestern Ontario: Am. Jour. Sci., vol. 249, pp. 66–71.

HOLMES, C. D. (1941) Till fabric: Geol. Soc. America Bull., vol. 52, pp. 1299–1354.

KNOX, K. S. (1952) The differentiation of the glacial tills along the north shore of Lake Erie: unpublished master's thesis, University of Western Ontario, 64 pp. Abstract published in Canada Mining Journal, 1953, vol. 74, p. 106.

KRUMBEIN, W. C. (1933) Textual and lithological variations in glacial till: Jour. Geology, vol. 41, pp. 382–408.

KRUMBEIN, W. C. and PETTIJOHN, F. J. (1938) Manual of sedimentary petrography: Appleton-Century Co., Inc., New York, 549 pp.

LEINZ, V. (1933) Ein Versuch Geschiedemergel nach dem Schwermineraliengehalt stratigraphisch zu gliedern: Zeitschr. Geschiebef. u. Flachlandg., Band 9, pp. 156–168.

PETTIJOHN, F. J. (1949) Sedimentary rocks: Harper & Bros., New York, 526 pp.

RICHTER, K. (1932) Die Bewegungsrichtung des Inlandeises reconstruiert aus den Kritzen und Langstachsen der Geschiebe: Zeitschr. Geschiebef. u. Flachlandg., Band 8, pp. 62–66.

RUSSELL, R. D. (1936) The size distribution of minerals in Mississippi River sands: Jour. Sedimentary Petrology, vol. 6, pp. 125–142.

SHEPPS, V. C. (1953) Correlation of the tills of northeastern Ohio by size analysis: Jour. Sedimentary Petrology, vol. 23, pp. 34–48.

TERZAGHI, K. and PECK, R. B. (1948) Soil mechanics in engineering practice: John Wiley & Sons, New York, 566 pp.

VON ENGELN, O. D. (1930) Type form of faceted and striated glacial pebbles: Am. Jour. Sci., 5th ser., vol. 19, pp. 9–16.

WENTWORTH, C. K. (1936a) An analysis of the shapes of glacial cobbles: Jour. Sedimentary Petrology, vol. 6, pp. 85–96.

——— (1936b) The shapes of glacial and ice jam cobbles: Jour. Sedimentary Petrology, vol. 6, pp. 97–108.

WHITE, G. W. (1951) Illinoian and Wisconsin drift of the southern part of the Grand River lobe in eastern Ohio: Geol. Soc. America Bull., vol. 62, pp. 967–977.

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FIGS. 1–3, DECEMBER, 1953

STYLOLITES AND OIL MIGRATION

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ABSTRACT

The formation of stylolite seams occurs due to the plastic nature of calcareous sediments and during the early period of their consolidation. Stylolitic development has no part in the process of removing petroleum products from calcareous source beds. The disconnected contraction cavities formed along stylolite seams may entrap petroleum in much the same manner as disconnected contraction cavities in dolomitic limestone as described specifically in connection with the Little Falls, N.Y. dolomite. When the contraction cavities are sufficiently large, numerous, and connected in the source beds, most of the petroleum may be expected to escape, under the right conditions. On the other hand, if such cavernous beds are structurally suitable they may hold the original oil or they may receive and retain migrating oil in large quantities especially if access channels exist.

The formation of stylolites in indurated petroliferous rocks has been cited in a recent paper by Ramsden (1952, p. 2185) as the cause for initiating the migration of petroleum from the source beds. The basis for this hypothesis arises from the presumption that stylolites originate in solid rock according to the concepts described in the pressure-solution theory by Stockdale (1922, 1926). The processes involved in the formation of stylolites by this theory require the removal of vast quantities of hardened rock by solution in the formation of stylolite seams. Stockdale (1926, p. 413) states that:

"solution within strata has reduced the thickness of certain rocks (especially limestones, dolomites and marbles) by amounts perhaps as high as 40 per cent or more in some instances."

By arbitrarily accepting the tenets of the pressure-solution theory, one has before him a powerful device for removing from soluble source beds a large part of the contained petroleum. However, this theory has been shown by the writer (1939, 1947, 1949, 1950) to contain many vital flaws and to be built upon unessential features of the stylolite columns and seams. Consequently, the application of the principals of this theory to the formation of stylolites and to the economically very important process of oil migration certainly does not appear to be justified even though it offers a most alluring picture of initiating oil migration to those who have but a meager acquaintance with only a few occurrences of stylolite seams.

The occurrence of petroleum in stylolitic formations would naturally arouse many speculations as to the economic significance of their coexistence. The role of stylolites and the fundamental processes by which they originate are, no doubt, of some importance to the accumulation or non-accumulation of petroleum and natural gas; but a thorough understanding of the actual post-depositional sedimentary processes during the still plastic state of the muds is of very great importance.

Two examples will be used to illustrate these situations. The first of these represents the occurrence of a hard *carbonized* bitumen in the crystal-lined cavities of the Little Falls, New York, dolomite of upper Cambrian age, figure 1. This formation is noted for its excellent doubly terminated clear quartz crystals which are frequently found in the bitumen-lined cavities. At other times only dolomite and calcite crystals line the cavities where the indurated

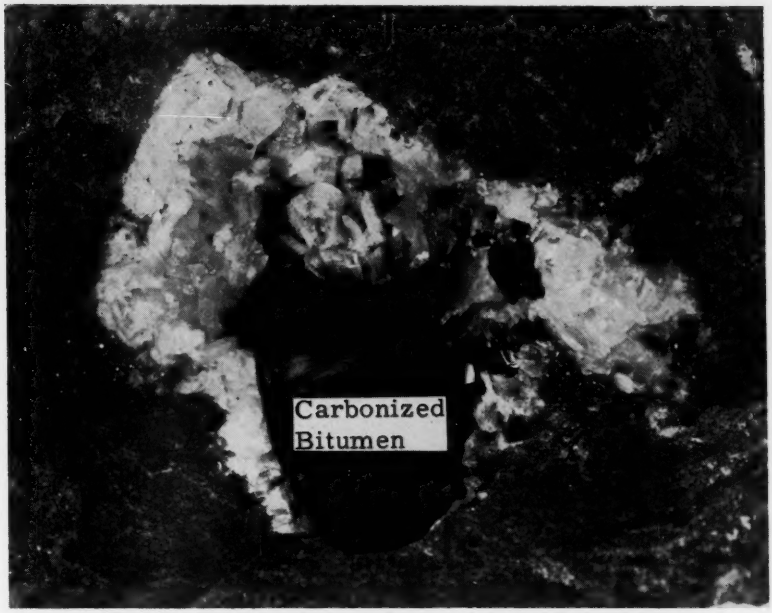

FIG. 1.—Cavity in the Little Falls, New York dolomite (upper Cambrian) which is lined with dolomite crystals (white) and contains a large piece of carbonized petroleum (black). ×2.

petroleum occurs as films, or as globular or irregular masses, resting on or around the crystals. Occasional cavities are free from bitumen.

The cause of the cavernous nature of similar rocks has been considered to be solution of the solid rock. This, however, does not appear to be the answer, for the cavities are in general isolated from one another and furthermore there are no visible solution effects associated with them. The carbonate rocks undoubtedly represent chiefly chemical precipitates which were originally an extremely fine-grained to colloidal mud and were associated with a large quantity of water. In view of these conditions, the escape of the water during the period of compaction, especially after the material had obtained some degree of firmness or rigidity, resulted in a three-dimensional shrinkage or contraction thereby creating the many scattered cavities which became lined with crystals from mineral matter held in the saturated aqueous solutions still present and which occupied the shrinkage cavities. The petroleum in the original muds was in part removed with the discharge of the water during the early stages of compaction and in part retained in the masses of the sediments which developed the cavities and finally a large part of the retained petroleum became entrapped within the cavities along with the residual water. During the long time since deposition, and probably at times subjected to relatively high temperatures, the petroleum became indurated and carbonized through the loss of the volatile parts which eventually escaped along with the originally entrapped water. If the nature of the carbonate sediments had permitted the escape of the water

FIG. 2.—Stylolite column from an oil well core showing dolomite crystals attached to the flutings. Specimen obtained at a depth between 8,900 and 9,000 feet in Anderson County, Texas from the Rhodessa formation of the lower Glen Rose of Camanchean age (Cretaceous). ×1.65

uniformly throughout the period of compaction the fluid oil probably would have been largely eliminated with it.

In the second example an outstanding occurrence of a stylolite seam shows on the one hand important features concerning the origin of the stylolite seams and on the other the significance of stylolite seams in their relation to the occurrence of petroleum.

The specimen was obtained from the Rodessa formation of the lower Glen Rose (Cretaceous) or Comanchean age at a depth of between 8,900 and 9,000 feet in Anderson County, Texas. Such a clear-cut stylolite seam does not appear to have been recorded previously from a depth even approaching this value although there is no reason why stylolite seams should not persist to very great depths.

An examination of the specimen shows

FIG. 3.—Enlarged area of Fig. 2 showing well-developed dolomite crystals which grew in a contraction cavity between the fluted walls of the stylolite seam. ×4.75

clearly that a cavity of at least a quarter-inch in width existed between the two sides of the stylolite seam. That a definite separation between the sides of the seam was present is clearly evident from inspecting the illustrations, figures 2 and 3. The curved crystals of dolomite, which have grown in the open space created by contraction are clearly shown in the photographs to be resting upon and attached to the flutings of the column. There is no evidence for the removal of rock material by solution or any other process. The adjoining part of the seam, were it available, certainly would show the same or similar conditions on the surface of the flutes as have been so frequently observed in the field by the writer in other instances. The cavities formed by continued contraction of the plastic muds on the two sides of stylolite seams during their formation are either devoid of a crystal lining or filled, in varying degree, with carbonates. Many sections cut across stylolite columns or seams show that the contraction

ranges in widths up to three-quarters of an inch. Such examples although reasonably abundant have been overlooked by the proponents of the pressure-solution theory. The history of the specimen shown in figures 2 and 3 is straightforward and simple. The stylolite was developed in the unconsolidated sediment according to the contraction-pressure theory and after the penetrating process had ceased the contraction of the material in the seam continued with further dewatering thereby causing a separation at places along the contact of the stylolite seam.

In both cases cited the predominant process is the contraction during the period of dewatering of the sediments. Under one set of conditions many cavities result, while under another stylolites, and under still another cone-in-cone (Shaub, 1937) result. In the event the carbonate rocks are petroliferous and the cavities are discontinuous, as in the Little Falls dolomite, the petroleum products are, in part at least, trapped in the many small openings. On the other hand, if such cavities and those formed around stylolite seams are sufficiently connected, and contain or receive petroleum in suitable geologic structures, an economic source of oil may be had.

REFERENCES

RAMSDEN, R. M. (1952) Stylolites and oil migration: Am. Assoc. Petroleum Geologists Bull., vol. 36, pp. 2185–2186.

SHAUB, B. M. (1937) The origin of cone-in-cone and its bearing on the origin of concretions and septaria: Am. Jour. Sci., vol. XXXIV, pp. 331–344.

——— (1939) The origin of stylolites: Jour. Sedimentary Petrology, vol. 9, pp. 47–61.

——— (1947) Coal partings in stylolite seams: Jour. Sedimentary Petrology, vol. 17, pp. 114–118.

——— (1949) Do stylolites develop before or after the hardening of the enclosing rock?: Jour. Sedimentary Petrology, vol. 19, pp. 26–36.

——— (1950) Microstylolites in pre-Cambrian quartzite: A discussion: Jour. Geology, vol. 58, pp. 650–652.

STOCKDALE, P. B. (1922) Stylolites: their nature and origin: Indiana Univ. Studies, vol. 9, Study 55.

——— (1926) The stratigraphic significance of solution in rocks: Jour. Geology, vol. 34, pp. 399–414.

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FIGS. 1–7, DECEMBER, 1953

SOME TRANSVERSE STYLOLITES

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ABSTRACT

Numerous stylolites are developed at high angles to bedding along joints in the near-reef limestone beds of the Bell Canyon formation at the front of the Guadelupe Mountains, Texas and New Mexico. Pressure and solution, after lithification, is clearly the cause of these secondary features.

INTRODUCTION

Stylolites have been the subject of several papers during recent years (Stockdale, 1943, 1945; Goldman, 1940; Shaub, 1939, 1949; Blake and Roy, 1949; Prokopovich, 1952). Various methods and times of stylolite formation have been proposed, varying from primary as proposed by Prokopovich (1952); penecontemporaneous as proposed by Shaub (1939) to late secondary as discussed by Stockdale (1943) and Blake and Roy (1949).

Blake and Roy (1949) describe transverse stylolites in Jurassic, Cretaceous and Pennsylvanian Formations of Colorado. Prouty (1952) has described transverse stylolites from Ordovician rocks of eastern Pennsylvania.

During field work in the Guadalupe Mountains during 1950 and 1952, the writer observed several outcrops of transverse stylolites in the rocks of the Permian Delaware Mountain group. They were observed in the Pinery limestone in Pine Spring and McKittrick Canyons; in the flaggy limestones beneath the Lamar limestone in McKittrick Canyon; and in the Lamar limestone at the mouth of Big Canyon (fig. 1).

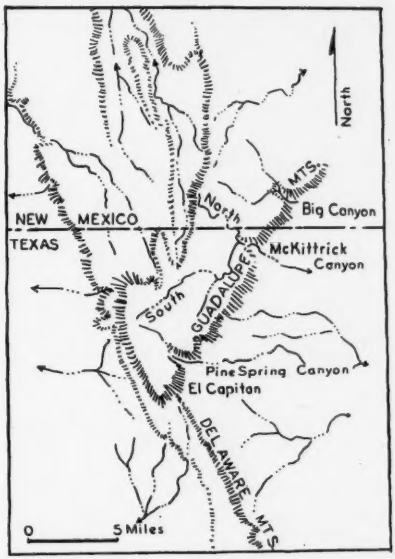

FIG. 1.—Index map of southern Guadalupe Mountains, Texas and New Mexico.

OBSERVATIONS

Pine Spring Canyon.—Perhaps one of the most instructive of the several outcrop areas, and an outcrop that clearly indicates a secondary origin of the observed stylolites, is in the near-reef facies of the Pinery member of the Bell Canyon formation in Pine Spring Canyon near the southern end of the Guadalupe Mountains (fig. 1). The locality is immediately above the "pothole" along the canyon floor (King, 1948, Pl. 3; U.S.G.S. Guadalupe Peak Topographic Sheet), at the top of what is locally called the "Roman Stairs," a small fall developed over well-bedded Pinery limestone.

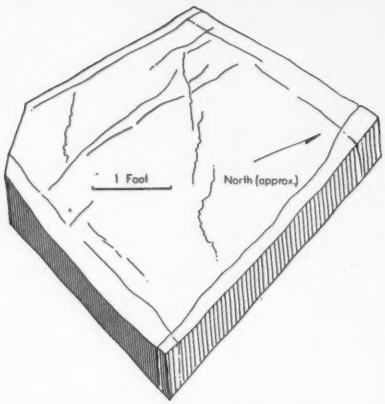

FIG. 2.—Block diagram of bedding surface in Pinery limestone showing transverse stylolites arranged diagonally to more recent major joints. Pine Spring Canyon, southern Guadalupe Mountains, Texas.

The Pinery limestone at this locality is a compact, semilithographic, dark blue-gray limestone stratified in two- to six-inch beds that exhibit lenticular and wavy bedding and contain chert nodules. The limestone beds are separated by thin beds of silty and sandy limestone up to half an inch thick. The rocks were deposited at the base of the Capitan reef scarp during development of that celebrated reef.

Numerous transverse stylolites are arranged in zones strongly suggesting tension joints (fig. 2). They are traceable for from 1 foot to 9 feet over bedding surfaces on the canyon floor and in places were observed to cross joints of other directions. The stylolite seams form angles from seventy to ninety degrees with the bedding surfaces and can be traced vertically across as much as 5 feet of strata. Some bend around chert nodules, and cut across thin stringers of silty limestone between more pure limestone beds.

Both pillar and conical stylolites are outlined by a clay seam along the suture which, at the crest, is about 1 mm thick. The pillars rarely exceed 2 inches, and the conical protuberances rarely exceed three-quarters of an inch long (figs. 2, 3).

A significant feature of these stylolites is their development along previously developed joints. The attitudes of 39 stylolite seams were determined at the above locality (table 1) and plotted as a joint "rose" (fig. 4B). The trends are bimodal, but this may be the result of the small size of the sample (Pincus 1951, pp. 81–129). The stylolite seams are parallel joints measured by P. B. King (1948, Plates 20, 21; fig. 4B) in Pine Spring Canyon and surrounding area. It is evident from a comparison of the two diagrams (figs. 4A and 4B) that the stylolite seams are developed along a single joint set and that the modal directions are approximately N 45° W and N 55° W.

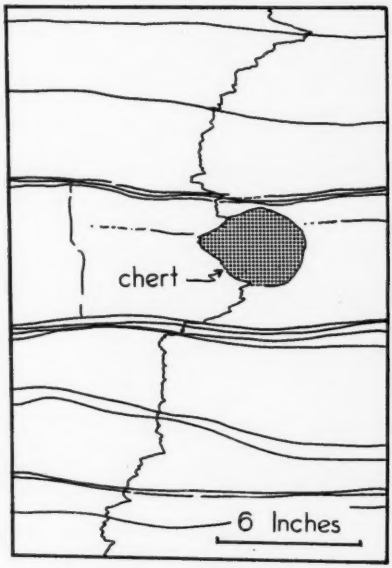

FIG. 3.—Diagram of transverse stylolite, taken from photograph, showing relation of seam to stratification and chert nodule. Pine Spring Canyon, southern Guadalupe Mountains, Texas.

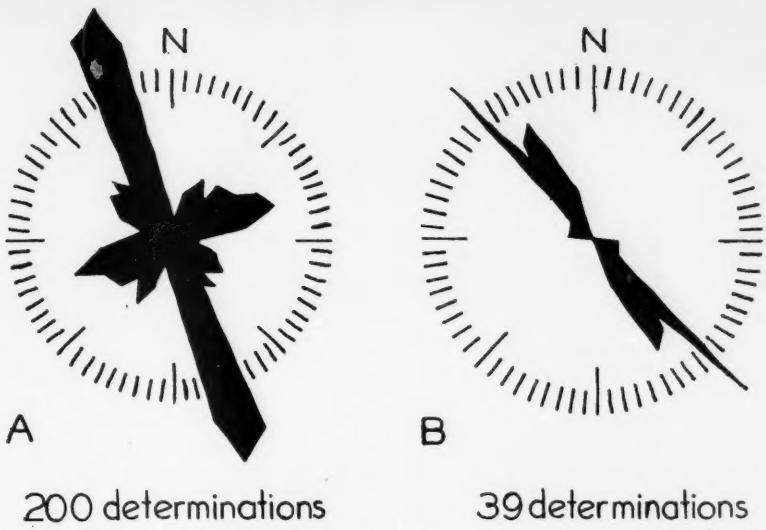

FIG. 4.—Orientation diagrams. A. Joints in Pine Spring Canyon area (after King, 1948). B. Stylolite seams in Pine Spring Canyon area.

In addition to the stylolitic joints, three other sets of joints were measured in the Pine Canyon area (fig. 4A). One of these lies essentially at right angles to the stylolites and exhibits a bimodal grouping at approximately N 30° E and N 50° E. This is probably the oldest set, for it has been affected by the development of stylolites, which in turn, have been offset by two sets of later joints.

Two other sets of joints, with northwest and east-northeast trends (fig. 4A), are dominant in the area. Apparently they are related to the major faults of the region (King, 1948, pp. 116, 124; Plates 20, 21). These are probably the youngest joints in the Guadalupe Mountains. Apparently they are more or less unrelated to the stylolites of the northwesterly trending joints.

TABLE 1.—*Observed trends of stylolite seams in the Pinery limestone in Pine Spring Canyon, southern Guadalupe Mountains, Texas*

Direction	Number of observed seams
N 70° W	0
N 65° W	3
N 60° W	8
N 55° W	7
N 50° W	5
N 45° W	13
N 40° W	2
N 35° W	1
N 30° W	0

McKittrick Canyon.—Another area of transverse stylolites is in the south wall of McKittrick Canyon (fig. 1) about a hundred yards below the junction of North and South McKittrick Canyons, near the valley floor. The stylolites occur in fine-grained, medium-bedded, gray Pinery limestone.

Bedding plane stylolites with columns ranging up to one inch high are abundant. Conical, pillar, and intermediate columns occur on a single bedding plane.

Well developed transverse stylolites are abundant in limestone beds draped over a small mound near the canyon floor (fig. 5). Columns of the transverse stylolites average about a half inch

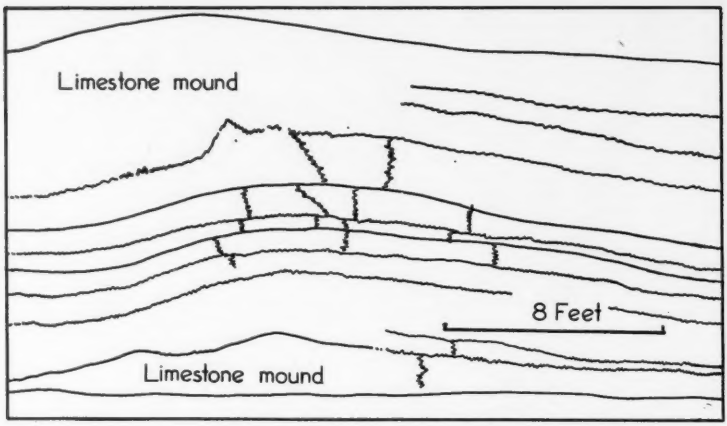

FIG. 5.—Diagram of south wall of McKittrick Canyon near junction of North and South McKittrick Canyons, showing relation of bedding and transverse stylolites to massive limestone mound in Pinery limestone.

long, with a maximum up to one inch. Clay of the stylolite is dark-gray; it is thickest at the apices of the columns where it is approximately 1 mm thick. The following table gives the attitude of the stylolite seams and of the columns.

TABLE 2.—*Attitude of transverse stylolite seams and columns in Pinery limestone, McKittrick Canyon, southern Guadalupe Mountains, Texas*

Attitude of seam		Attitude of columns	
Strike	Dip	Direction	Angle
N 50° W	88° SW	N 57° E	2° SW
N 51° W	89° SW	N 55° E	5° SW
N 35° W	83° NE	N 61° E	4° SW
N 40° W	Vertical	N 60° E	3° SW
N 50° W	89° SW	N 58° E	4° NE
N 42° W	86° NE	N 63° E	2° SW
N 37° W	88° SW	N 58° E	2° SW
N 51° W	41° SW	N 55° E	4° SW

The attitudes of these stylolites are essentially like those of Pine Spring Canyon. The columns of the McKittrick Canyon stylolites are not perpendicular to the planes of the seams, but rather lie at slight angles. The arithmetic mean of the trends of the seams is N 44° W. The expected direction of column penetration would thus be N 46° E, or approximately at right angles to the seam. The stylolite columns, however, have an average trend of N 58° E., or a difference of approximately 12 degrees from the anticipated direction. Presumably, the observed direction of penetration is approximately the direction of greatest compression.

Numerous examples were observed where transverse seams cross bedding-plane stylolites at angles of 40 to 90 degrees. At one place (figs. 5, 6) four transverse stylolites intersect a single bedding plane stylolite within a horizontal distance of 10 feet. In each case, the transverse stylolite is offset at the bedding plane. The displacement ranges from 2 to 5 inches. Columns of the bedding plane seams have been badly fractured and sheared by relative movement along the transverse columns. It is obvious that the bedding plane stylolite is older, and that the rock was well lithified before the development of the transverse seams.

Mouth of McKittrick Canyon.—A third interesting exposure of transverse stylolites is at the south side of the mouth of

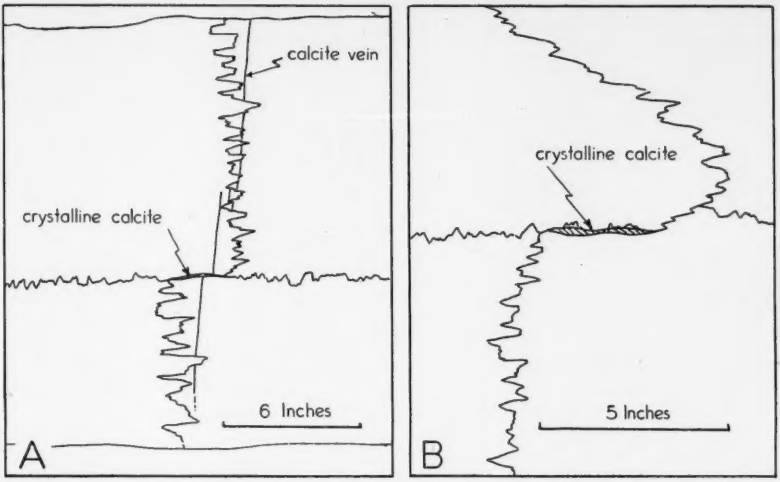

FIG. 6.—Detail sketch of transverse and bedding stylolites in Pinery limestone, McKittrick Canyon.

McKittrick Canyon, in the base of the thin limestone tongue between the Lamar and Rader limestone members of the Bell Canyon formation (unnamed flaggy limestone of King, 1948). The seams occur in a yellowish-gray silty limestone, transitional from underlying sandstone into relatively pure limestone. Here the columns average approximately a quarter inch high, and the stylolite seams are nearly at right angles to the bedding. Table 3 summarizes the data on these and other transverse stylolites in Big Canyon.

Seven transverse stylolites were observed within a distance of 20 feet along the outcrop. All are nearly parallel and probably were developed along the same joint set that displays stylolites in Pine Spring Canyon and at the junction of North and South McKittrick Canyons.

In contrast with the locality near the junction of North and South McKittrick Canyons, the columns at this locality are developed at right angles to the seam, indicating that the compressive force acted at right angles to the stylolite seam.

Big Canyon.—Transverse stylolites are developed over the crest of a sharp

TABLE 3.—*Attitudes of stylolite seams and columns in the mouths of McKittrick and Big Canyons, southern Guadalupe Mountains, Texas*

Location	Attitude of seam		Attitude of columns	
	Strike	Dip	Direction	Angle
McKittrick Canyon	N 56 W	84 NE	N 38 E	1 SW
McKittrick Canyon	N 50 W	85 NE	N 39 E	1 SW
Big Canyon	N 48 W	72 SW	N 45 E	13 NE
Big Canyon	N 51 W	84 SW	N 37 E	2 NE

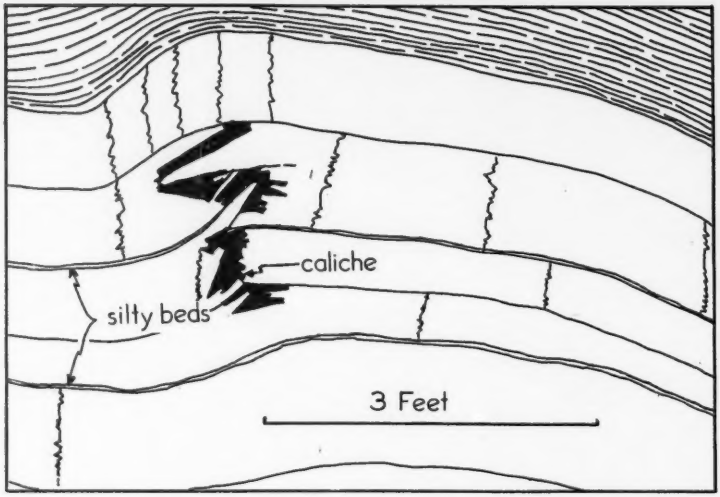

FIG. 7.—Diagram of transverse stylolites over massive limestone mound in Lamar limestone, mouth of Big Canyon, southern Guadalupe Mountains, New Mexico.

mound in the lower Lamar limestone of the Bell Canyon formation, on the north side of the mouth of Big Canyon, approximately two hundred yards north of the Stanley ranch house. They are particularly abundant in medium-grained, gray bituminous limestones, where the beds have been folded and dip as much as 23 degrees off the mound. There is a general tendency for the seams to be parallel, indicating probable joint control, but the stylolite columns plunge, more or less radially, in the direction of dip off the dome.

CONCLUSIONS

Stylolites in the Guadalupe Mountains are developed both parallel and at high angles to stratification. The transverse stylolites show a consistent trend, except where they are modified by local irregularities. These irregularities in structure have resulted in stylolite columns that are not perpendicular to the stylolite seam. This indicates that part of the original compressive force, in certain occurrences, was a vector of load acting laterally and downward along arched strata.

With minor modifications, the stylolite seams have an average trend of approximately N 51° W, approximately that of a set of joints recorded by King (1948, Plates 20, 21). It is concluded that the joints were avenues of ground water circulation during compressive stress, and that the joints were locally modified into stylolite seams.

Similar occurrences of transverse stylolites along joints have been described and documented by Blake and Roy (1949). Prouty (1952) also suggests that transverse stylolites observed by him are parallel major joints, though his conclusions are not as well documented as those of Blake and Roy. Prokopovich (1952) describes transverse stylolites in the Malm limestone of southwestern Germany. He concludes that the stylolites "occur independent of the tectonic framework. . . ." He points out, however, that the stylolite seams are not always parallel. This suggests that they are fre-

quently parallel and joint controlled. He does not give adequate documentation to support his conclusions.

The occurrence of stylolites along joints at high angles to stratification indicate a late secondary origin of the seams. This is particularly true where the stylolites have a constant attitude regardless of the age of the country rock. Under certain circumstances it seems possible that sediments may have undergone solution to develop stylolite seams, as proposed by Prokopovich (1952), but it seems improbable that the sutures are entirely a result of surface solution. There is no evidence that stylolites were developed at the sea floor, as suggested by Prokopovich (1952), other than a gross surficial resemblance of the seams to erosion forms. Evidence of burial of irregularly etched and eroded lime muds is lacking.

Only in the case of transverse stylolites, where the relative age of jointing can be ascertained, can the time of origin of seams be approximated. Horizontal stylolites may have resulted from solution of either soft or lithified sediment after burial. In the latter sense, stylolites might be thought to be either late penecontemporaneous or early secondary structures. The presence of a film of residual clay in the stylolites leaves little doubt that they are the result of solution and not of simple plastic flow as proposed by Shaub (1939, 1949).

REFERENCES

Blake, D. B. and Roy, C. J. (1949) Unusual stylolites: Am. Jour. Sci., vol. 247, pp. 779–790.

Goldman, M. I. (1940) Stylolites: Jour. Sedimentary Petrology, vol. 10, pp. 146–147.

King, P. B. (1948) Geology of the southern Guadalupe Mountains, Texas: U. S. Geol. Survey Prof. Paper 215, 183 pp.

Pincus, H. J. (1951) Statistical methods applied to the study of rock fractures: Geol. Soc. America Bull., vol. 62, pp. 81–130.

Prokopovich, N. (1952) The origin of stylolites: Jour. Sedimentary Petrology, vol. 22, pp. 212–220.

Prouty, C. E. (1952) Unusual stylolites in Ordovician limestones of eastern Pennsylvania: The Compass, vol. 30, pp. 11–14.

Shaub, B. M. (1939) The origin of stylolites: Jour. Sedimentary Petrology, vol. 9, pp. 47–61.

——— (1949) Do stylolites develop before or after hardening of the enclosing rock?: Jour. Sedimentary Petrology, vol. 19, pp. 26–36.

Stockdale, P. B. (1922) Stylolites; their nature and origin: Indiana Univ. Study 44, pp. 1–97.

——— (1943) Stylolites, primary or secondary?: Jour. Sedimentary Petrology, vol. 13, pp. 2–12.

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FIGS. 1–3, DECEMBER, 1953

THE SEDIMENTS OF LAKES FLORENCE AND LUCY, CENTRAL FLORIDA

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ABSTRACT

Sediments from Lake Florence, one of the many soft water lakes of central Florida (Orange County), are described in detail. It is noted that sediments from several other soft water lakes of the same region are essentially of similar character. Sources of the sediments are examined and speculations relating to the origin of the lake basins and the times of their becoming sites of lakes are made. Deposition is shown to have been extremely slow and the organic matter is suggested to have reached an advanced stage of decomposition.

INTRODUCTION

Lakes Florence and Lucy are small lakes in the western part of Orange County, central Florida. The former has an area of about 50 acres, the latter about 70 acres. These two lakes are typical of the hundreds of small to large bodies of water which are so abundant over the Ridge section of the peninsula. Most are relatively shallow with the maximum depths generally less than 35 feet. The maximum depths of Lake Florence (figs. 1, 3) are less than 30 feet and at the time of writing, May 1953, are about five feet lower than at the time the samples were acquired. Most, perhaps all, of the basins in which the lakes lie are considered to have formed by solution of the underlying limestones and their levels are generally adjusted to the local ground water tables. However, it is possible that at times in some lakes their water levels may be above the local water tables as they may be to some degree perched and they are certainly perched with respect to the deep underground waters in that most, perhaps all, could be drained by drilling wells through the underlying materials to the cavernous limestones below. There are many basins that contain no water. This is due either to the bottoms of these basins being higher than the highest levels of the local water tables, or in having outlets into the underlying limestones.

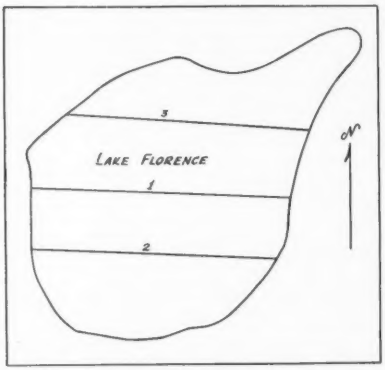

FIG. 1.—Outline of Lake Florence. The numbers 1, 2, and 3 indicate the positions of the three traverses. At the time of writing the margins of the lake have been narrowed which in some places is as much as 100 feet (May, 1953).

Solution of the underlying limestones which is considered responsible for most of the lake basins is considered to have been external on the top of the uppermost limestone, or internal. In the former case the surface of the ground subsided as the upper surface of the limestone was lowered by solution. In the latter case there was a more or less long period during which the limestones became cavernous and the sequal to this development was collapse and formation of a basin. It

is known that small basins have been formed in this way in Florida. It is also possible that some basins developed behind seashore dunes as the last of the Pleistocene submergences came to an end and Florida rose to something like its present elevation. Both forms of solution are believed to be in progress now as is thought to be shown by the calcareous content of the waters of the many large springs that issue from the underlying limestones. That the limestones are honeycombed by large and small solution cavities is proven by experiences in drilling as at times a single stroke of the drill may sink from several inches to several feet, by the fact that several cities formerly discharged their sewage into wells that had been drilled into the underlying limestones and also disposed of excess water in the same way, and by the many large springs that issue from the limestones of which three: Rock, Sanlando, and Wikivi, are only short distances to the north.

Solution on the upper surface of the topmost limestone permitted, and probably still permits, escape of the waters and the dissolved solids to lower levels. Insoluble residues were and probably still are left behind and these ultimately led and now lead to the protection of the upper surface from solution. The insoluble residues together with overlying materials followed the surface of the limestone downward, thus producing depressions on the surface. If the insoluble residues prevented downward passage of the surface waters, the depressions filled with water and lakes came into existence. If downward passage of water was not prevented, the basins remained without permanent water and this would be the case if the bottom of any basin was above the lowest level of the local water table. Collapse of the roof of a cavern and sealing of the outlet below also would lead to the formation of a basin which might become the site of a lake. It is known that basins of this origin in some cases have steep sides, but it is thought that some may not be unlike the basins formed by solution of the top surface of the topmost limestone. It is probable that nearly every lake of central Florida could be eliminated by drilling a large diameter hole in its bottom.

Most of the lakes of central Florida are without outlet and few have indraining streams. Lake levels rise and fall with the rainfall of all lakes without outlet. Lake levels are annually highest shortly after the close of the rainy season. Levels rise with every big rain and levels are lowest at the end of the dry season in May or early June. Entrance of water into most lakes is by seepage, but some have indraining streams, springs, and there is some surface inflow during heavy rains.

Most of the lakes of central Florida are not deep. Even Lake Apopka, about seven miles northwesterly, with an area of more than 100 square miles, does not seem to have depths greater than 35 feet. The bottom muds of this lake are frequently stirred by storms so that the waters become so full of suspended matter as to be lethal to fish. A collapse basin in western Florida is said to have been sounded to a depth of 100 feet without touching bottom which makes the bottom considerably below sea level. Newspapers occasionally write of bottomless lakes which is one way of stating that the lakes have not been carefully sounded.

SOURCES OF THE SEDIMENTS OF LAKES FLORENCE AND LUCY

Materials surrounding lakes Florence and Lucy are sands, silts, clays, and peat. The sands are almost entirely vitreous quartz of angular shapes. Dimensions are mostly less than one-fourth millimeter. Some of the sands are not wettable (Jamison 1942, 1945) and thus float rather easily. The silts are also mostly quartz and there is really very little clay in any of the surrounding areas. Some organic matter floats from the shores and some doubtless is carried in by the winds. Organic matter disregarded, the quartz content of the sands over the areas surrounding the lakes generally exceeds 99

per cent. Small quantities of other minerals are present. Analyses of four samples of sands from the neighborhood of lakes Florence and Lucy made by Professor Stanley A. Tyler of the University of Wisconsin after elimination of the quartz by means of heavy liquids gave the results shown in table 1.

TABLE 1.—*Number of grains per hundred grains of the several kinds of heavy minerals*

Mineral	No. 1[1]	No. 2	No. 3	No. 4
Zircon	21	22	19	21
Sillimanite	12	8	10	7
Cyanite	2	6	4	1
Rutile	6	3	7	6
Staurolite	12	14	12	9
Tourmaline	5	7	4	4
Leucoxene	14	22	12	13
Ceylonite	x	x	x	x
Apatite		x		
Opaque minerals	28	18	31	39

[1] 1. Hill on west side of Lake Florence, 2 miles east of Ocoee, Fla.
2. Sand Lake, 4 to 5 miles southeast of Ocoee.
3. Fairvilla Road, 3 to 4 miles east of Lake Lucy.
4. Just south of Clarcona, 2 miles north of Lake Lucy.
x An occasional grain.

It should be noted that the figures given in the table are in terms of 100 grains of the heavy minerals, but that the total of heavy minerals in a sample is less than one per cent. The table shows that the most common heavy minerals are zircon, staurolite, leucoxene, and opaque minerals. It is possible that the leucoxene is a decomposition product of rutile. Noteworthy are the absences of garnet, hornblende, and epidote which Tyler found quite common in the sands off the east coast of Florida. The grains of staurolite and sillimanite are relatively large and somewhat angular with etching present on both minerals. The grains of zircon are well rounded. Places exist in Florida and in the sands of the east coast where heavy minerals are common, and even abundant, as near Starke in northeast Florida, at a place a little south of Jacksonville where the sands are worked for the heavy minerals and on the beaches in the vicinity of Saint Augustine and Melbourne. At these places the common heavy minerals are zircon, rutile, ilmenite and monazite.

Until very recently lakes Florence and Lucy had a dense growth of grass and reeds about their margins and this condition also existed over the shallow bottoms adjacent to the shores and still exists over those parts of the shores and shallow bottoms that have not been improved. As a consequence, little inorganic sediments other than fine particles of silt and clay dimensions were brought by inflowing waters to the bottom sediments. The non-wettable sands were readily floated in and it is probable that considerable sand thus entered the two lakes. Considerable sand and silt are now carried into the lakes by the common high winds and this probably was a source in the past although not to the extent as at present as the lands before cultivation were covered with vegetation of various kinds. The surrounding areas contain no calcareous materials and none enters the lakes. Hence, the waters are very soft and shelled invertebrates are rare. Less than a dozen thin-shelled mollusks have been seen.

The deposits of peat about some of the margins of the lakes and the bordering vegetation doubtless contributed some organic matter and some probably grew in the waters. There are doubtless planktonic organisms living in the waters and from these several sources were probably derived the organic sediments which cover the deeper parts of the bottoms.

SEDIMENTS OVER THE BOTTOMS OF THE LAKES

Three traverses for collection of samples were made across Lake Florence and one across Lake Lucy. The positions of the traverses across Lake Florence are shown on the map of that lake (fig. 1). The traverse across Lake Lucy is not shown as it was made to check with those made on Lake Florence. This traverse

was made from the McNutt landing to the D. P. Sias landing. The traverses across Lake Florence were made with reference to more or less permanent positions. No. 1 was made from the Twenhofel dock to the Schweiker dock, no. 2 from a position half way between the Twenhofel dock and the Millar dock to the Welles dock, and no. 3 was made from the Newberg dock directly east to the east side of the lake. The sediments collected on the three traverses were acquired with an Ekman dredge and were analyzed and studied in the laboratories of the University of Tulsa during the spring semester of 1950. The sediments from Lake Lucy were collected and analyzed in 1946 and 1947. As these check in all essential details with those from Lake Florence, data thereon are not presented. Sediments were also collected from Dream Lake on the north edge of the village of Apopka, about 10 miles north of Lake Lucy. Sediments were also acquired from Lake Apopka at a place about seven miles west of Lake Lucy.

The collections show that the sediments over the deeper parts of lakes Florence and Lucy are very black soupy materials and that these mantle the bottoms from about the depth of 20 feet to the greatest depths. The sediments on bottoms of the shallow waters adjacent to the shores are largely fine quartz sands which may be black from the content of organic matter. Where shores are composed of peat the adjacent sediments are fine, black gritty muds. The small thickness of sediments over the bottoms of both lakes is surprising and in both lakes it does not exceed two feet at the places where samples were taken over the deep parts of the two lakes. As the soupy materials have a water content exceeding 90 per cent, it follows that the thickness of solid sediments would not exceed three inches. The sampling shows that the soupy materials in both lakes are underlain by fibrous peat which in turn is underlain by sand showing that not too long ago the areas of lakes Florence and Lucy were not covered by lakes but by swamps. No data are known to the writer to place definitely the times when the change from swamp to lake took place.

TABLE 2.—*Percentage of organic and inorganic matter.*

Sample no.	Depth in ft.	Organic matter	Inorganic matter
1	7	0.8	99.2
2	12	1.8	98.2
3	13	2.5	97.5
4	15	2.1	97.9
5	18	1.1	98.9
6	18	0.6	99.4
7	15	1.4	98.6
8	16	0.7	99.3
9	17	1.0	99.0
10	18	7.3	92.7
11	21	2.4	97.6
12	26	39.3	60.7
13	26	23.2	76.8
14	25	43.1	56.9
15	24	20.9	79.1
16	15	2.4	97.6
17	11	2.1	97.9
18	18	3.6	96.4
19	21	3.4	96.6
20	26	35.4	64.6
21	25	30.8	69.2
22	24	34.0	66.0
23	12	1.9	98.1
24	12	2.1	97.9
25	19	4.3	95.7
26	23	20.5	79.5
27	25	46.3	53.7
28	25	47.3	52.7
29	24	28.8	71.2
30	25	53.1	46.9
31	26	50.3	49.7
32	21	4.4	95.6
33	18	3.5	96.5
34	15	2.8	97.2
35	10	7.4	92.6
36	9	2.0	98.0
37	6	1.1	98.9

A 10 to 20 gram fraction of each sample was dried to constant weight and then ignited to determine loss by ignition. This loss was estimated as organic matter. There may be a slight error in this estimation as some of the samples contained small quantities of probable clay minerals. What remained after ignition was separated into fractions based on dimensions by means of Tyler standard screen sieves. The results of the analyses are shown in tables 2 and 3.

TABLE 3.—*Mechanical analyses of the sediments. The inorganic sediments of each sample are considered as 100 per cent*

Sample no.	½ mm	¼ mm	⅛ mm	1/16 mm	1/64 mm	Pan
1	0	3.3	41.1	44.6	10.5	0.5
2	0	5.8	46.6	37.8	7.6	2.2
3	0	4.4	43.4	42.6	9.2	0.4
4	0	5.6	45.7	37.9	8.2	2.6
5	0	5.1	47.8	38.9	6.1	1.1
6	0	5.2	44.0	43.9	6.9	tr.
7	0	5.1	50.8	39.9	4.2	1.0
8	0	5.4	50.4	39.6	2.3	2.3
9	0	7.9	51.9	36.2	3.2	0.8
10	0	4.5	48.6	41.9	4.0	1.0
11	9	5.4	46.7	38.7	4.4	3.8
12	0	1.0	9.5	15.9	21.3	52.3
13	0	0.2	4.2	21.6	34.0	40.0
14	0	tr.	tr.	5.9	11.7	82.4
15	0	2.3	8.3	29.6	50.4	9.4
16	0	6.6	34.9	42.0	13.8	2.7
17	tr.	4.1	40.6	44.2	8.4	2.7
18	0	4.1	38.8	46.5	8.3	2.3
19	0	4.4	40.7	45.6	7.1	2.2
20	0	2.1	5.6	11.3	26.6	54.4
21	0	tr.	10.6	36.4	33.9	19.1
22	tr.	4.7	29.9	37.5	12.6	15.3
23	0	3.3	38.9	46.3	9.2	2.3
24	0	3.4	35.8	48.9	10.9	1.0
25	0	3.3	44.1	41.7	6.9	4.0
26	0	tr.	tr.	72.7	12.4	14.9
27	0	tr.	tr.	12.2	14.0	73.8
28	0	tr.	tr.	18.7	22.0	59.3
29	0	0.6	1.2	32.9	28.5	36.8
30	0	tr.	tr.	tr.	tr.	100.0
31	0	tr.	tr.	8.3	13.2	78.5
32	0	3.5	26.1	49.9	18.3	2.2
33	0	4.7	23.3	49.5	19.2	3.3
34	0	3.5	23.8	51.1	17.9	3.7
35	0	6.1	33.4	44.7	13.4	2.4
36						
37	0	4.7	22.1	40.7	31.6	2.9

Numbers 1 to 16 are from traverse 1, 17 to 24 from traverse 2, and 25 to 37 from traverse 3.

Several things in the analyses are noteworthy. They show that the organic content of the sediments from the deepest parts of the lake is very high and decreases very rapidly from the depth of about 20 feet to the shallow water at the shores, but some organic matter is always present. The quartz particles are invariably very clear, invariably angular from the dimensions held on the one-sixteenth millimeter screen to the smallest dimensions, but from the one-eighth to larger dimensions there are many rounded and frosted grains. There is obviously a mixture of quartz particles from many sources and of both long and short travel in a relative sense. In most cases all diameters are less than one-fourth millimeter and the greatest percentages are in the one-eighth and one-sixteenth millimeter grades. It is only over the deeper parts of the lake that particles of one-sixty-fourth millimeter or smaller dimension are important. The fraction left on the pan after separation of the larger dimensions was always white. Sorting of the sediments is good. Several cumulative curves are shown in figure 2

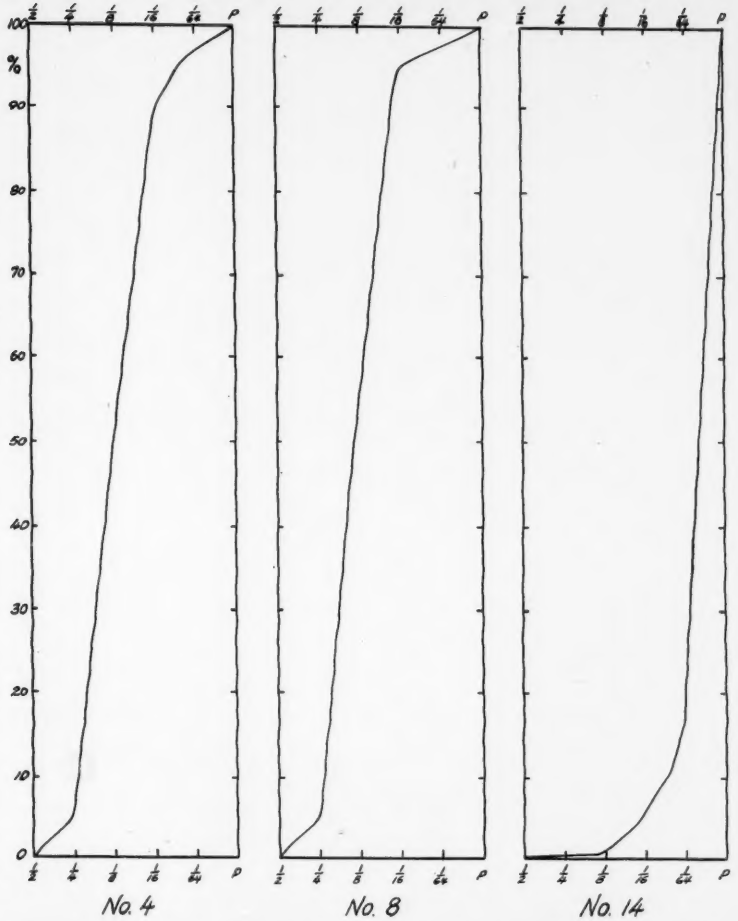

FIG. 2.—Cumulative curves of samples number 4, 8, and 14 of traverse 1. Number 4 is from the depth of 15 feet, number 8, from 16 feet and on the high area near the middle, and number 14 is from the deep place on the east side. The curves show fairly good sorting and also show that in the cases of number 4 and 8 the maximum quantities are in two grade sizes. Number 14 shows that nearly the whole of the sample is less than 1/64 mm in diameter.

and a cross section of Lake Florence with positions of the places of taking samples is shown in figure 3.

Lake sediments resting on fibrous peat which in turn rests on sand have been described by Davis as reversed deposits. The sequence of sediments in lakes Florence and Lucy are of this character as had already been pointed out by Davis for Lake Lucy, and it is obvious that the areas of both lakes were swamps before they became lakes. What was the sequence

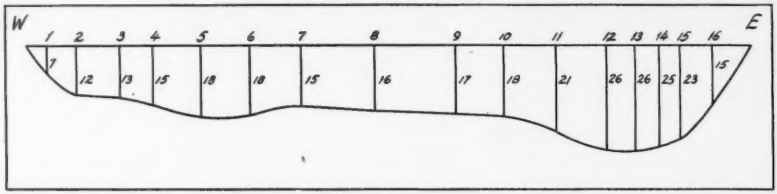

FIG. 3.—Number 1 traverse across Lake Florence from the Twenhofel dock on the west to the Schweiker dock on the east. The length of the traverse is approximately 1450 feet. Depths of water are indicated in feet. The diagram shows that the bottom of the lake along this traverse is uneven and that the deepest part of the lake is on the east side.

of conditions that made this possible? Davis gives eight conditions that might be responsible for the changes of water level. Only three of these are considered to have any application to the facts that are known with respect to the two lakes. These are as follows: (1) increase in rainfall with concomitant rise of water tables and lake levels, (2) subsidence of the basins, and (3) clogging of outlets into the underlying limestones. Although possible, the first explanation is not favorably considered. Forsaith and Roe referred the rise of water level in the lakes they studied to rapid closing of underground outlets. This explanation may be applicable to the lakes studied by them, but the writer doubts the applicability to lakes Florence and Lucy. The second explanation is favorably considered. During the external solution of the underlying limestones there was a time when the subsidences to which the basins may be due began. In the beginning no swamps existed but as subsidence continued swamps would necessarily come into existence and peat deposits would begin to form. Continued subsidence led to the swamps becoming covered with permanent water and the areas then were covered with shallow lakes and these deepened with continued solution of the top surface of the underlying limestones. With the development of a permanent water cover to eliminate the plant growths, the deposition of lacustrien sediments began.

Davis has noted that eight of the 22 lakes studied by him have reversed deposits and it is probable that there are many more. Davis gives two explanations which he considers the probable explanations of this condition, namely, a "regional rise in both ground and surface water; and a reduction in the amount of underground drainage." The present writer does not consider either the correct explanation.

Sediments collected in many fresh and soft water lakes of Wisconsin have as their important organic constituent a pale greenish yellow gel. This is very rare in any of the sediments so far collected in the Florida lakes. The organic matter of the sediments from the Florida lakes is black, very finely divided, and seems to be so highly oxydized that the hydrogen and oxygen contents are low and the carbon high. On ignition after drying, the organic matter from the soft water lakes of Wisconsin generally burned explosively, whereas the organic matter in the sediments from lakes Florence and Lucy merely became red on ignition and required a relatively long time to burn. It seems obvious that the organic sediments from the lakes of the two regions are quite different in composition.

Treatment of the sediments from the soft water lakes of Wisconsin with hydrocarbon solvents always yielded substances which were hydrocarbons. Nothing of this character was acquired by treatment of the sediments from Lake Florence with the same solvents. It is thought that the differences in the char-

acter of the organic sediments from the lakes of the two regions is due to the 12-month bacterial activity in Lake Florence against the much shorter annual time in the Wisconsin lakes.

Skeletal matter of sponges and tests of diatoms are rather common in the sediments of the soft water lakes of Wisconsin, but neither of these was seen in the sediments collected from lakes Florence and Lucy. Such are probably present, particularly the latter, as deposits of diatomaceous materials are not uncommon in this part of Florida.

It has been stated on a previous page that the thickness of soupy materials that has accumulated since the basins became occupied by lakes is about two feet. These have a water content of around 90 per cent and after dewatering would make a solid deposit between two and three inches. How long a time was required to deposit this thickness of sediment? It is not known, but the rate of deposition must have been extremely slow. Inorganic sediments would have had to have passed through a screen of reeds and grasses and the rate of supply of indigenous organic sediments could hardly have been great. If it be assumed that the rate of deposition approximated one-twentieth of an inch per annum only 500 to 750 years would have been required. This seems too short a time. However, there are no known data permitting an assumption, but one millimeter per annum seems large. At any rate, it seems likely that the development of lakes Florence and Lucy was a comparatively recent event, perhaps took place in the last 10,000 years.

REFERENCES

DAVIS, J. H., JR. (1946) The peat deposits of Florida, their occurrence, development, and uses: Florida Geol. Survey Bull. 30, 247 pp.

FORSAITH, V. C. (1942) A report on some allochthonous peat deposits of Florida: Bot. Gazette, vol. 62, pp. 32–52.

JAMISON, V. C. (1942) The slow reversible drying of sandy surface soils beneath citrus trees in central Florida: Soil Sci. Soc. America Proc., vol. 7, pp. 36–41.

——— (1945) The penetration of irrigation and rain water into sandy soil of central Florida: Soil Sci. Soc. America Proc., vol. 10, pp. 25–29.

ROE, E. C. (1935) Mud Lake, a Florida algal lake: unpublished bachelor's thesis, Princeton Univ.

TYLER, S. A. (1934) A study of sediments from the North Carolina and Florida coasts: Jour. Sedimentary Petrology, vol. 4, pp. 3–11.

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FIGS. 1–3, DECEMBER, 1953

LATIN SQUARE EXPERIMENTS IN SEDIMENTARY PETROLOGY

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ABSTRACT

The Latin square is a statistical device which provides a random distribution of observations or measurements. It is useful in sedimentary petrology for exploratory study of relations among samples, techniques, and operators in field and laboratory studies.

INTRODUCTION

The Latin square is an arrangement of letters in a square such that each letter occurs once in each row and column. They were first used in agricultural experiments, where the squares represented plots of ground with different fertilizer treatments. The Latin square arrangement permits evaluation of row and column effects (related to varying soil fertility) as well as "treatment" effects represented by the letters. From this earliest use the Latin square was extended to a variety of applications in other fields. The purpose of this paper is to list some uses in sedimentary petrology

Latin squares represent a three-factor analysis of variance model. They belong in the category of randomized block experiments in distinction to factorial experiments. In Latin squares the columns, rows, and "treatments" represent the three factors, and the model permits separate evaluation of the variance associated with each factor. The theory of the Latin square is given in many statistics texts, but the reader is especially referred to Dixon and Massey (1951, p. 140) who give full details on computation. An introductory treatment with an example on sphericity measurements is given in Krumbein and Miller (1953).

EXAMPLES OF LATIN SQUARE EXPERIMENTS

Latin squares make no provision for evaluation of interactions. (See Griffiths and Rosenfeld, 1953, for a discussion of interactions in a factorial experiment.) Despite this, Latin squares serve well as exploratory devices for rapid evaluation of main effects. They are particularly useful for preliminary study of factors later to be included in more detailed factorial experiments. They are also useful and stimulating in settling questions which arise during class discussions. Does the mean sphericity or roundness differ significantly for a sample if 25, 50, 100, or 200 pebbles are measured? Does the number of garnet grains in a total count of 300 vary significantly from place to place on the same heavy mineral slide? Do operators differ significantly in their interpretation of lithology from electric logs?

These and many other questions can be answered to a first approximation for any given set of samples in a surprisingly short time, and the results may be made the basis for design of more detailed experiments as class projects. Inasmuch as the Latin square includes three factors in each experiment, a single project can test several related questions at once. Most of the writer's experiments involved differences between samples, techniques, and operators, using 4×4 Latin squares. Six combinations are possible among columns, rows, and letters, depending upon which factor is assigned to each. Interesting variants are had by using the letters for samples in one case, techniques in another, and operators in a

third. In 4×4 Latin squares there are four each of operators, techniques, and samples. The samples may in some instances be four splits of the same master sample. Latin squares range in size to 8×8 or larger, but 4×4 and 5×5 squares appear to be most popular.

There is a certain formality about designing experiments for the Latin square. A null hypothesis is set up to the effect that there are no significant differences between samples, operators, or techniques at the 5 per cent significance level. The experiment is then performed, and the hypothesis is tested by comparing the variances of the three main effects with the "residual" variance left after the main effects are separated out. If the ratios of the main effects to the residual exceed the selected critical level for the degrees of freedom in the experiment, the hypothesis is rejected. Critical values are given in tables of the F function, as included in Dixon and Massey (1951, p. 310). Three experiments are described here as examples.

Percentage of Garnets in Heavy Mineral Samples.—The question was raised whether the percentage of garnets observed in certain heavy mineral slides varies significantly with the total number of grains counted. Four sandstone separates from four different outcrops were used in the test. Each of four operators was to start at the center of the slide, count either 50, 100, 200, or 400 grains in sequence, and record the number of garnets observed. The null hypothesis is that there are no significant differences in the three main effects at the 5 per cent significance level.

In this experiment it was decided to assign samples to rows, technique (number of grains counted) to columns, and to randomize the operators as treatments. Figure 1, top, shows the percentage of garnets observed. Percentage was used because of varying sample size, but statisticians generally recommend the arc sine transformation with percentage data before analysis of variance (Snedecor, 1946, p. 447). The lower diagram in Figure 1 shows the transformed data, with its analysis of variance in the table at the base of the figure. The computations follow a standard procedure, given in detail by Dixon and Massey (1951, p. 139). Briefly, the sums of squares (SS) are found by squaring all items and subtracting a correction factor. The degrees of freedom (DF) for the main effects are one less than the number of rows, columns, and "treatments," leaving 6 degrees of freedom for the residual. The variance is found by dividing SS by DF; finally, the F ratio is obtained by dividing

A. RAW PERCENTAGE DATA

LETTERS ARE OPERATORS

SAMPLES	TECHNIQUE (NO. OF GRAINS) 50	100	200	400
1	B 0.0	C 17.0	D 12.0	A 10.2
2	C 16.0	D 18.0	A 13.5	B 13.4
3	D 0.0	A 1.0	B 0.0	C 2.0
4	A 10.0	B 8.0	C 13.0	D 8.0

B. TRANSFORMED DATA (ARC SINE)

A = 64.3
B = 37.9
C = 77.2
D = 61.8
241.2

B 0.0	C 24.4	D 20.3	A 18.6	63.3
C 23.6	D 25.1	A 21.6	B 21.5	91.8
D 0.0	A 5.7	B 0.0	C 8.1	13.8
A 18.4	B 16.4	C 21.1	D 16.4	72.3
42.0	71.6	63.0	64.6	

ANALYSIS OF VARIANCE

SOURCE	SS	D.F.	VARIANCE	F	
Technique	122.09	3	40.70	2.38	NS
Samples	826.88	3	275.63	16.13	**
Operators	201.41	3	67.14	3.93	NS
Residual	102.51	6	17.09		
TOTAL	1252.89	15			

$F_{.95}(3,6) = 4.76$; $F_{.99}(3,6) = 9.78$

FIG. 1.—Raw and transformed data on garnet percentage in sandstones. Operators Christensen, Danehy, Hefner, Probst.

each main variance by the residual variance. The critical values of F are given in the figure, and the observed values are keyed as non-significant (NS), significant at the 5 per cent level (one star), or significant at the 1 per cent level (two stars). As the results show, the samples are significantly different, but the operator and technique effects are not. Hence, the null hypothesis is accepted for these two effects, and rejected for the samples.

This experiment differs from the corresponding factorial experiment in that the main effects are tested directly against the residual, without an intermediate testing of interactions. The relatively high F value for operators suggests that in a more detailed experiment this factor may be significant. However, there is an unassigned source of error due to variation in the exact part of the slide measured by each operator. This could be tested by assigning fixed "cells" on the slides and testing differences among them.

Sand-Shale Ratio from Electric Logs.—In connection with regional studies the question was raised whether students read values from electric logs critically enough to assure no operator effects. Four electric logs of a Cretaceous stratigraphic interval about 800 feet thick in four counties were measured by four operators. The row effect in the experiment was assigned as a test of "skill improvement" to see whether the group improved or changed its mass technique with experience. The Latin square and analysis of variance table are shown in Figure 2. As before, the null hypothesis is that none of the main effects is significant at the 5 per cent significance level. As the table shows, the operator and skill effects are non-significant, whereas the samples (logs) are significantly different at the 1 per cent level. In this experiment the null hypothesis is accepted for the non-significant effects, and rejected for the samples.

It is to be noted that the data of this second experiment are expressed as ratios, so that the arc sine transformation

OPERATORS

SAMPLES	"SKILL"	I	II	III	IV	
A = 0.56		A 0.14	B .28	C .19	D .49	1.10
B = 1.13		B .29	C .15	D .31	A .13	0.88
C = 0.65		C .15	D .48	A .14	B .28	1.05
D = 1.56		D .28	A .15	B .28	C .16	0.87
3.90		0.86	1.06	0.92	1.06	

ANALYSIS OF VARIANCE

SOURCE	SS	D.F.	VARIANCE	F	
Operators	0.0077	3	0.0026	<1	NS
"Skill"	.0104	3	.0035	1.06	NS
Samples	.1611	3	.0537	16.27	**
Residual	.0198	6	.0033		
TOTAL	0.1990	15			

FIG. 2.—Sand-shale ratios from four electric logs. Operators Christensen, Danehy, Krumbein, Probst.

is also appropriate. However, if a minimum value of 2 feet is used as a unit of measurement, the 800-foot sections yield an n of the order of 400. Proportions based on large n values tend to be normally distributed (Johnson, 1949, p. 165), and the same results are obtained in terms of hypothesis acceptance or rejection whether the transformation is used or not. In fact, the raw data of Figure 1 also yield the same result as the transformed data.

Thickness of Beds in Negaunee Iron Formation.—This is an example of field use of the Latin square. The question was whether the Negaunee Iron formation is homogeneous in thickness of jasper and hematite beds over an exposure about 60 by 20 feet at Jasper Knob, Negaunee, Michigan. The Latin square was laid out as in Figure 3, with four rows arranged along the continuous beds, four columns laid normal to the bedding, and operators randomized according to letters. The arrangement used here is the "King's knight" Latin square, in which the letter *A* moves about like a knight on a chessboard. Each operator

measured 25 beds by marking them on adding machine tape, and the average thickness in mm for each sample was computed. Figure 3 lists the data for the jasper beds; similar tests were run for the hematite. As the analysis of variance shows there is no significant "intra-bed" variance (rows), inter-bed variance (columns), or operator effect. The null hypothesis was accordingly accepted for all three. An average thickness of 4.26 mm may accordingly be taken as an unbiased estimate of the mean for the homogeneous population at this exposure. The residual variance may also be taken as an estimate of the variance of sample means for the population.

Other Applications.—In addition to many exploratory experiments in field and laboratory, Latin square designs may be interlocked with factorial designs. The bed thickness study, for example, was interlocked with a two-factor experiment to test for significant row-column interaction (there was none). Two or more Latin squares may themselves be replicated, (Patterson, 1939 p. 172) with interesting results. The form of the Latin square also lends itself to randomizing operations in field and laboratory.

OPERATORS: CHRISTENSEN, DANEHY, DEWEES, HEFNER

BEDS ACROSS \ ALONG BEDS				
A	D 4.2	A 7.3	B 9.1	C 5.9
B	B 8.2	C 6.1	D 6.5	A 1.8
C	A 3.5	B 3.8	C 8.0	D 5.9
D	C 7.5	D 6.2	A 4.5	B 3.4

ANALYSIS OF VARIANCE

SOURCE	SS	DF	VARIANCE	F
COLUMNS	15.58	3	5.193	1.10 NS
ROWS	4.40	3	1.467	<1 NS
OPERATORS	14.34	3	4.780	1.01 NS
RESIDUAL	28.32	6	4.720	
TOTAL	62.64	15		

FIG. 3.—Average thickness of 25 jasper beds, Negaunee Iron Formation, Negaunee, Michigan.

CONCLUDING REMARKS

This brief introduction to Latin squares in sedimentary petrology is intended to call attention to an experimental design which deserves attention as an exploratory research tool and for teaching purposes. It should be mentioned that the 5×5 square is generally more satisfactory than the 4×4 square, but the simplicity and compactness of the latter favor its use for first-order studies. In this use the square is not intended as a substitute for more detailed experiments. It is suggested that the reader interested in applying Latin squares supplement this expository treatment with additional reading on the theoretical foundation of the design (Kempthorne, 1952). The examples cited here are not intended to establish generalizations. The same results may not be had with other operators or samples.

REFERENCES

DIXON, W. J. and MASSEY, F. J. (1951) Introduction to statistical analysis: McGraw-Hill Book Co., New York.

GRIFFITHS, J. C. and ROSENFELD, M. A. (1953) A further test of dimensional orientation of quartz grains in Bradford sand: Am. Jour. Sci., vol. 251, pp. 192–214.

JOHNSON, P. O. (1949) Statistical methods in research: Prentice-Hall, New York.

KEMPTHORNE, O. (1952) The design and analysis of experiments: John Wiley and Sons, New York.

KRUMBEIN, W. C. and MILLER, R. L. (1953) Design of experiments for statistical analysis of geological data: Jour. Geology, vol. 61, pp. 510–532.

PATTERSON, D. D. (1939) Statistical technique in agriculture research: McGraw-Hill Book Co., New York.

SNEDECOR, G. W. (1946) Statistical methods: Collegiate Press, Ames, Iowa.

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DECEMBER, 1953

REVIEWS

Clay Mineralogy by Ralph E. Grim, 1st ed., 1953. Pp. viii+384; tables 46; figs. 121; appendix 1; 6×9 ins., cloth. McGraw-Hill Book Co., 330 West 42d St., New York. Price, $9.00.

Clay Mineralogy by Ralph E. Grim is the first book in the English language to treat the mineralogy of clay in a comprehensive coverage. It assumes therefore the eminence of another milestone in clay science to follow such important publications in English as the pioneer paper, The Kaolin Minerals, by Ross and Kerr (1931); Ross and Hendricks', Minerals of the Montmorillonite Group (1945); and the more specialized, "X-ray Identification and Structure of Clay Minerals" by Brindley, *et al.* (1951).

Professor Grim is to be congratulated on having done an excellent and outstanding job of achieving his objective as stated in the preface "to summarize data on the structure, composition, properties, occurrence, and mode of origin of the various clay minerals whose identities have been reasonably well established." His style is clear and easily readable, straight-forward, and concise, but not too brief. The subject matter is well-organized, thoroughly covered, and logically presented. Students beginning the study of clay mineralogy will find the book readily understandable at their level, although somewhat tedious in detail in several places, and the advanced worker finds the essence of the important papers on the subject extracted faithfully and unbiasedly, with full bibliographic reference to the original sources. The degree of completeness of the bibliography is to be especially commended.

Fourteen chapters comprise the book. In Chapter One Dr. Grim discusses the implications of the word clay, rather than merely defining it which can become an exercise in semantics (Keller, 1949). The diverse properties which characterize clay materials are reviewed. In Chapter Two the historical growth of the modern structural concept of clay minerals is traced chronologically, and by way of an early chemical approach.

In Chapter Three the clay minerals are classified on the modern structural basis as crystalline two-layer, three-layer expanding and non-expanding, mixed layer sheets, chain structure types, and amorphous. Present-day clay mineral nomenclature, and questionable and discredited clay mineral names are discussed. Beidellite is placed in the latter category, which may be debated by some workers. Grim follows the usage of the name halloysite, with the degree of hydration appropriately described, in conformity with the feeling expressed by the 1950 International Congress of Soil Science.

A thorough, well illustrated, easily read treatment of the fundamental structure of the clay minerals is given in Chapter Four. Latest published information on triclinic kaolinite, the double silica layer in anauxite, oriented water layers in halloysite, and tubular morphology of halloysite due to unequal sized layers, is reviewed. The structure of montmorillonite proposed by Hoffman, Endell, and Wilm is preferred over that of Edelman and Favejee, although the latter is given unstinted coverage. The illite structure is clearly contrasted with those of montmorillonite and muscovite. Separate descriptions of chlorite, vermiculite, the sepiolite-palygorskite-attapulgite, and mixed-layer minerals complete this important chapter.

The X-ray diffraction data in Chapter Five are taken largely from the volume by Brindley, *et al.*, which is duly acknowledged by Grim. Beautiful electron micrographs of the clay mineral groups, reproduced from the work of Bates and the API publication (1950), are given in Chapter Six. Professor Grim neglected to emphasize that the "run of mine" elec-

tron micrographs of clay minerals, like most amateurs' snap-shot pictures, do not result in the superb photographs which are selected for publication.

Ion exchange in its diverse ramifications and complications is well summarized in Chapter Seven, although the great detail (desirable) is rather tedious reading. Cationic exchange has been far better explored than has anionic exchange. The work of soil chemists such as Kelley, Marshall, Mukherjee, Jenny, and others, and the numerous references to soil science literature testify to the importance of clay mineralogy in agronomy, and to the vast contribution from that area.

Chapter Eight treats of the clay-water system at temperatures below 300°C., which involves plasticity, Thixotropy, green bond and structural strength, swelling, and other features of clay wetted by water. The Hendricks and Jefferson proposal for adsorption by clay of oriented water is presented, along with criticisms of it, and alternative proposals. Dehydration of clays at higher temperatures, including their artificial pyrometamorphism and inversion to other minerals, and a good discussion of differential thermal analysis and its possibilities and limitations continues in Chapter Nine. The personal researches of Grim with colleagues, who include Cuthbert, Rowland, Bradley, and others, become increasingly evident to the reader, and enhance the power and conviction of the presentation.

Chapter Ten treats of clay mineral-organic reactions. Organic matter in soils, and analytic techniques (including staining) based on clay mineral-organic reactions highlight this topic. A vast technology which would combine inorganic clays with organic reagents appears to lie temptingly unexplored beyond this chapter.

The optical properties of fired and unfired clays, and relationships of refractive index to immersion media and orientation are covered in Chapter Eleven. Miscellaneous properties of clay minerals, such as solubility in certain reagents, electrodialysis, infrared absorption spectra, surface area, and densities comprise Chapter Twelve.

The synthesis and hydrothermal origin of clay minerals are well summarized in the first part of Chapter Thirteen. A rather detailed outline of soil types and environments of their formation with relation to weathering conclude the chapter. Chapter Fourteen continues with the same title as that of Chapter Thirteen, "The origin and occurrence of the clay minerals." Recent and ancient argillaceous sediments, and various types of clay-bearing rocks are discussed in terms of what data are available. The need for more petrologic data on argillaceous rocks is made obvious. Much more is yet to be learned about the geology and petrology of clay rocks.

A useful appendix of chemical analyses precedes an adequate index.

Very few typographical errors or inconsistencies, especially for a first edition, were noted. The good quality paper and typography, and convenient placing of illustrations and footnotes are consistent with the first quality work by the author. The price of the book is $9.00, a price which will be not low to many students in many fields desiring the book.

Grim's *Clay Mineralogy* will be a boon to teachers of the subject who have had scant time to cover the formidable literature of clay mineralogy which is spread across the publications in mineralogy, geology, soil science, physical and colloid chemistry, ceramics, soil mechanics, etc. College students in all those fields now have an opportunity to learn authoritatively what has been discovered about clays in allied areas. Courses in clay mineralogy will probably be offered in more colleges now that this text is available.

On the debit side of the ledger, this reviewer would like to have seen a more specific or formal chemical treatment in the formation of clay by both processes of weathering and synthesis, especially to balance the considerable space given

to the descriptive part of soil formation. Some colleagues in geology have expressed the wish that a determinative scheme for the systematic running down of an "unknown" clay specimen and identification of it had been included in the book.

Dr. Grim's book is excellent, and he has set a high standard for future publications in clay mineralogy. It is noteworthy that clay minerals were the most poorly known and most misunderstood of the groups of abundant minerals before 1930, but within twenty years so much important information has been accumulated that a separate book is taken to cover it. Most of the work on clay minerals has been off the traditional track of external goniometry, physical properties, and conventional mineralogic techniques. Classic mineralogy receives new vigor from this youth which has quickly come of age. Not long ago clay minerals were spoken of as being complex in contrast to simple (?) feldspars, quartz, amphiboles, and pyroxenes; the seeming relative simplicity of those other groups is vanishing as they are being studied in closer detail.

Professor Grim has done the broad science of mineralogy a real service by introducing in it a first quality book on an important separate mineral group.

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REFERENCES

American Petroleum Institute (1950) Electron micrographs of clay minerals: Am. Petroleum Inst. Proj. 49, Prelim. Rept. No. 6.

BRINDLEY, G. W. (1951) X-ray identification and crystal structure of clay minerals, in Brindley, G. W. *et al.*, Experimental Methods: Mineralog. Soc. Great Britain Mon., pp. 1–31.

KELLER, W. D. (1949) Clays—general survey: Encyclopedia of chemical technology, New York, pp. 24–37.

ROSS, C. S. and KERR, P. F. (1931) The kaolin minerals: U. S. Geol. Survey Prof. Paper 165E.

ROSS, C. S. and HENDRICKS, S. B. (1945) Minerals of the montmorillonite group: U. S. Geol. Survey Prof. Paper 205B.

The Permian reef complex of the Guadalupe Mountains region, Texas and New Mexico by N. D. Newell, J. K. Rigby, A. G. Fischer, A. J. Whiteman, J. E. Hickox, and J. S. Bradley, 1st ed., 1953. Pp. 308; figs. 85; pls. 32; $5\frac{1}{4}\times9\frac{1}{2}$ ins., cloth. W. H. Freeman and Co., 549 Market St., San Francisco. Price, $7.50.

This is a fine treatment of a fascinating subject. The work may appear at first sight to be a research memoir rather than a college text, but we might venture to predict that many parts of it may become "required reading" for future students of sedimentation and stratigraphy. The first chapters are devoted to the regional paleogeographic setting, general stratigraphy, and paleontology. In chapter four the reef complex and its associated sedimentary phases are dealt with in great detail. The particular importance of submarine slumping of the sides of reefs and the resultant sedimentary structures are clearly illustrated. Evidence of sedimentary volcanism is brought forth and the interesting sandstone dikes are illustrated. Submarine landslides are compared with subaerial ones in some detail and one may wonder perhaps if some of the structures attributed to density currents today may not have originated as massive slides which became fluid and thus were actually density currents only in the middle and lower course of their flow. Possibly we have lost sight of some of the earlier evidence for submarine landslides such as was summarized by Stanley Gardiner in 1915 and also by the present writer (1947).

The authors courageously adopt new terms where they are required, such as Grabau's old term *calcarenite*, but they do not adopt them for the pure joy of it and do so only where obviously necessary.

They appear to find unnecessary difficulty, however, over the well recognized term *euxinic*, meaning, of course, a deep stagnant basin and its deposits, for which they find "no obvious advantage," but do not give the original reference. The term is widely used today (see, for example, Kuenen, 1950). One may also refer to the older works of 25 years ago by Krejci-Graf (1930, p. 39) and Arkanguelsky in German and Russian. As regards the Delaware Basin, Wells (1952) has suggested that the term "paraeuxinic" would be appropriate, since this basin was apparently not very deep.

In the study of the reefs themselves the remarkable similarities with present-day reefs come out very clearly. However, there are of course notable differences and these are not ignored. Present day reef terminology appears to be appropriate and they follow the suggestion of Preston Cloud (1952) in using the term "organic reef" for all reef structures affected by wave action, restricting the term "bioherm" to similar masses of "doubtfully wave resistant nature." In the Permian the most important reef type appears to have been the barrier and after that the various patch reefs, but one should not forget that the term patch reef was introduced by Umbgrove for a specific type of reef occurring on the continental shelf which arises in an irregular flat-topped patch. In dimensions such patch reefs range from a few hundred feet to perhaps a mile or two in diameter. The larger patches grade with some genetic changes into what Niermeyer originally called the "plaatrif" and which the present writer prefers to translate as "platform reef." These gigantic reef patches range up to 20 miles or so across and are rather beyond the dimensions of the simple patch. In contrast the terms "coral head" or "coral pinnacle" should be restricted to small growths of reef material rising in the lagoons to form a pedestal, often somewhat overhanging at the top and generally not more than a hundred feet in diameter. The clear distinction between these three reef types, all characteristic of shelf regions, should not be forgotten. It is also apparent that coral heads rising in a sheltered lagoon may not cause the waves to break in which case they would fall into Cloud's restricted "bioherm"; the distinction at this stage is not very clear. Many of the dome-like reefs of the Paleozoic appear to have begun in this manner and to have finished with a rounded top, well covered by Darwin's expression "reef knoll." On the other hand the term "table reef" used by Tayama in 1935 appears to have no distinction not covered already many years before by the terms of Niermeyer and Umbgrove.

The authors' figure 53 (page 106), "Diastrophic factor in reef growth," appears likely to be copied in many textbooks of the future. Unfortunately, it does not display perhaps a stage D which would show the shoreward transgression of a barrier reef complex over lagoonal deposits (of say 100 foot depth) during a stable period following rapid upgrowth and development of the barrier, which would occur as a result of a quick subsidence of the reef or rapid rise of sea-level. The stage D suggested above would correspond to Henson's "transgressive reef." This work makes little or no reference to the role of eustatic movements in contrast to the diastrophic except in a footnote (on page 106) where the eustatic role is implied, though not actually stated. Clearly subsidence was a major influence in the Delaware Basin, but the contrasting effect of eustatic change would also have deserved some mention, especially for a period such as the Permian with its wide-spread paleoclimatic changes and related facies displacements.

The highly porous nature of the reef structure is clearly brought out, and the leaching of a reef flat is correlated with exposure to rainfall at low tide. This appears unlikely. Recently the writer, in company with M. A. Carrigy, collected water from pools or directly in beakers during rain storms on reefs and found that in no case, was there a low pH indicating an acid environment. Owing to the

saturation of the atmosphere with salt in this area, the pH remained high and, in reef pools, was always over eight. Even though the salt water became notably diluted, it could never be said to be acid. Likewise spray with CO_2 dissolved in it does not seem to be an acid medium. Again this was tested with alkaline results. The only spots where a low or acid pH was encountered was in very small reef pools filled with sand or algae. Here the activity of bacteria and of blue green algae, in creating for themselves an acid micro-environment, seems important in etching the limestone. This was recently confirmed on Tahiti by Revelle, Rotschi, and the writer.

In chapter six the role of diagenesis is well developed. Here the Correns definition is followed, taking diagenesis as all post-depositional processes connected with compaction, hardening and alteration. The role of varying pH in silicification and calcification is brought out, and the importance of bacteria in this connection is also mentioned. The problem of dolomitization is perhaps less satisfactorily treated and although the primary deposition of dolomite is regarded as doubtful, the actual nature of the replacement process is left completely open. There is no reference or testing of the interesting hypotheses of Skeats, Udluft and Reuling. Under these theories, submarine dolomitization appears to take place in the reducing environment of a closed lagoon assisted by increased CO_2 pressure and slightly elevated temperature, with free access of magnesium-rich sea water. This condition would seem to be ideally fulfilled in the case of this Permian reef complex. This problem was recently reviewed by the writer (1950, p. 385).

In chapter seven, the paleoecology is treated in a masterly fashion. An extension of the study to a wider field might improve the paleoclimatology, but perhaps this is asking too much of a regional study.

Finally, in chapter eight, the importance of the reef complex in the formation of oil is outlined, though perhaps a little too briefly. Worth noting is the relationship of calcium carbonate solution and replacement, especially at the reef margin of the back reef facies.

A compliment is due to the publishers, the W. H. Freeman Company, who in recent years have produced some notable contributions to geological teaching and higher research by seeking out and obtaining the services of authors with advanced and energetic views. The printing is good, the plates excellent, the diagrams numerous and clear. It may be remarked that far too many institutions of learning are still using text-books which contain hardly any recognition of scientific progress during the last three or four decades. Inevitably there is a time lag between research, initial publication, criticism, testing, and acceptance into recognized texts, but there seems little excuse for letting that time lag build up to something like half a century. So congratulations to Dr. Newell and his team and to their excellent publisher, and not least to the Humble Oil and Refining Company which made the publication possible.

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REFERENCES

CLOUD, P. E. (1952) Facies relationships of organic reefs: Am. Assoc. Petroleum Geologists Bull., vol. 36, pp. 2125–2149.

FAIRBRIDGE, R. W. (1947) Coarse sediments on the edge of the continental shelf: Am. Jour. Sci., vol. 245, pp. 146–153.

——— (1950) Recent and Pleistocene coral reefs of Australia: Jour. Geology, vol. 58, pp. 330–401.

GARDINER, J. S. (1915) Submarine slopes: Geog. Jour., vol. 45, pp. 202–319.

KREJCI-GRAF, K. (1930) Grundfragen der Oelgeologie: Stuttgart (Enke), 182 pp.

KUENEN, PH. H. (1950) Marine geology: John Wiley and Sons, New York, 568 pp.

WELLS, J. W. (1952) Note on the Mississippian and Permian reef suites: Jour. Geology, vol. 60, pp. 97–98.

Principles of Invertebrate Paleontology by Robert R. Shrock and William H. Twenhofel, 2nd ed., 1953. Pp. 816; figs. 488; 6¼×9¼ ins., cloth. McGraw-Hill Book Co., Inc., 330 West 42nd St., New York. Price, $12.00.

Invertebrate Paleontology (Twenhofel and Shrock), first edition, appeared in 1935. At that time it was a welcome addition in a field which was without a modern text. The reviewer's first thought was to compare the 1953 edition of *Principles*, with the first edition in order to note the changes; however, the second edition is not a revision but a new book, rewritten, reorganized, and enlarged.

After an introductory chapter of 27 pages the various groups of invertebrates are discussed first by phylum, then by class, and finally by order. An introductory portion of each chapter considers the morphology of the phylum. This is followed by a discussion of classification in which details concerning classes and orders may be found. In some instances families are briefly discussed. The closing portion of each chapter deals with such subjects as ecology, geologic history, and evolution. The treatment of morphology and classification is unusually well done and thorough. The illustrations are numerous, well executed, and clearly labeled. They are mostly pen-and-ink drawings, but numerous photographs have been used to good advantage. Charts showing the geologic range of various groups are included in most chapters. Also, diagrams showing the phylogenetic relationship of several groups are used effectively.

The classification used in any text is always subject to criticism and there will always be differences of opinion between specialists on this subject. The authors have used the most up-to-date suggestions of specialists on the various groups. In doing this they recognize 22 phyla and arrange them in a manner conforming to the most recent biologic information. This results in placing the Annelida after the Mollusca and separating them from the usual treatment with Vermes. Also this results in chapters on Hemichordata, and Conodontophoridia. A fuller than usual treatment is given the Insecta and several other groups of arthropods, though the ostracodes are rather briefly discussed.

It is possible to differ with the details of classification, but this reviewer believes that the authors are to be praised for attaining such complete coverage of all invertebrate phyla.

The book will serve as a useful text in a year course in elementary paleontology. Also, graduate students and professional geologists will find it to be a valuable reference book for a long period of time.

HAROLD W. SCOTT
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Lexico Sedimentalogico by F. G. Bonorino and M. E. Teruggi, 1953. Pp. 164; figs. 15; tables 4. Instituto Nacional de Investigaciones de las Ciencias Naturales and Museo Argentino de Ciencias. Naturales, Buenos Aires.

Although *Lexico Sedimentalogico* is written in Spanish and may not be used widely on that account, it is easy reading and no extensive knowledge of the language is required to understand the work.

The book is opened by a prologue by Dr. A. E. Riggi, Director General of the Institute and Museum, followed by a preface of four pages stating the objectives of the work. The 28 page introduction discusses the methods of nomenclature and the grade scales of clastic sediments (table 1 shows six grade scales). Comparison is made of the Wentworth scale with that of the Servicio Technico Minero de Venezuela and one proposed by the authors (table 2). The proposed terminology does not greatly depart from that of Wentworth except that Spanish equivalents for the English terms are used. Illustrations are of cumulative curves, histograms, triangular diagrams, thin sections, and some structural and depositional features of sedimentary rocks.

The Lexicon in which 816 sedimentary terms are defined composes most of the

work. In general the term is given in Spanish, followed by the English equivalent, which in many cases is followed by the German equivalent. Then follows the definition which may cover as much as a page. The following are examples: Torrente de Barrio: I. *mudflow*, A. *Schlammstrom;* Lutita (L. *lutus fango*): I. *shale*, A. *Tonschiefer*.

There are two indexes. In the first the English terms are given followed by the Spanish equivalents, and in the second the German terms are followed by the Spanish equivalents. This arrangement adds immensely to the possible use of the book.

This work should be extensively used by, and of great assistance to, American, Canadian, and English geologists working in our sister governments south of the United States. It is hoped that the English-speaking geologists working in these countries will acquaint themselves with its usefulness. Geologists owe a debt of gratitude to the authors for preparing the work.

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SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS

ANNOUNCEMENT OF 28th ANNUAL MEETING ST. LOUIS MISSOURI, APRIL 12–15, 1954

The 28th annual meeting of the Society of Economic Paleontologists and Mineralogists will be held next April 12–15 in St. Louis, Missouri. The meeting will, as usual, be held jointly with the American Association of Petroleum Geologists and the Society of Exploration Geophysicists. Technical programs will be held in the Opera House and commercial and educational exhibits will be displayed in the Convention Hall of St. Louis' Kiel Auditorium. There will be two joint sessions with A.A.P.G., one session of mineralogic papers, one session of paleontologic papers, and two symposia. The Jefferson has been designated as the headquarters hotel.

Committee chairmen are as follows: General Chairman for the 1954 S. E. P.M. meeting, N. S. HINCHEY, Department of Geology, Washington, University, St. Louis, Missouri; Chairman of Technical Program, H. A. IRELAND, Department of Geology, University of Kansas, Lawrence Kansas; Head, Symposium on Carbonate Rocks, R. J. LEBLANC, Shell Oil Company, Houston, Texas.

SOCIETY NOTES—COUNCIL, COMMITTEES AND REPRESENTATIVES

Council of the Society of Economic Paleontologists and Mineralogists
(March 1953–April 1954)

President: Harold N. Fisk, Humble Oil and Refining Company, Houston, Texas.

First Past-President: Clifford C. Church, Tide Water Associated Oil Company, San Francisco, California.

Second Past-President: Thomas H. Philpott, The Carter Oil Company, Shreveport, Louisiana.

Vice-President: W. Thomas Rothwell, Jr., Richfield Oil Corporation, Long Beach, California.

Secretary-Treasurer: Samuel P. Ellison, Jr., University of Texas, Austin, Texas.

Editor, Journal of Sedimentary Petrology: J. L. Hough, University of Illinois.

Editor, Journal of Paleontology: Grover Murray, Louisiana State University, Baton Rouge, Louisiana.

The entire council acts as an advisory body to the American Association of Petroleum Geologists Committee on National Responsibility.

Directors of American Geological Institute
- Senior: T. H. Philpott
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NEWS AND NOTES

Notice.—News items for publication in this section in future issues are solicited. They should be addressed to: The Editor, Journal of Sedimentary Petrology, Department of Geology, University of Illinois, Urbana, Illinois.

Establishment of the Gulf Coast Section of the Society of Economic Paleontologists and Mineralogists has been approved by the S.E.P.M. Council. This is to be the second Section of the Society; the other is the Pacific Section, headed by Professor ORVILLE BANDY of the University of Southern California. The steering committee for the organization of the Gulf Coast Section is composed of: STUART A. LEVINSON, Chairman; CHARLES W. STUCKEY, Vice-chairman; FRED L. SMITH, Jr., Vice-chairman; JACK O. COLLE, Secretary; FRANK V. STEVENSON, Treasurer; and MORTON B. STEPHENSON, Vice-treasurer. An advisory committee is composed of OLIN G. BELL, JULES BRAUNSTEIN, MARCUS A. HANNA, HENRY V. HOWE, URBAN B. HUGHES, JAMES L. MARTIN, WINNIE MCGLAMERY, and LOUISE JORDAN.

Dr. G. W. BRINDLEY of the physics department, University of Leeds, England, has joined the staff of the Pennsylvania State College as research professor of mineral sciences.

Dr. J. L. HOUGH, Editor of the *Journal*, is taking leave from the Department of Geology, University of Illinois, for two years to represent the University in a project in India. He will organize the Department of Geology in the new Indian Institute of Technology, at Karaghpur, near Calcutta. The project, which will involve eight senior staff members from various departments at Illinois, is set up under a three-way arrangement between the Government of India, The U. S. State Department (Technical Cooperation Administration), and the University of Illinois.

Dr. RALPH E. GRIM, Research Professor of Geology, University of Illinois, and Associate Editor of the *Journal*, will serve as acting Editor beginning with the March, 1954 issue and continuing for two years during the absence of Editor Hough.

The appointment of Dr. H. RICHARD GAULT to serve as Executive Secretary of the Division of Earth Sciences, National Research Council, has been announced by the National Academy of Sciences Council. Dr. GAULT'S appointment was effective July 1, and he and the new Divisional chairman, Dr. FRANCIS BIRCH, Sturgis-Hooper professor of geology at Harvard University and eminent geophysicist, are organizing the new program of the Division.

The Second National Conference on Clay Minerals was held at the University of Missouri, Columbia, Missouri on October 14–16. The Conference was sponsored by the Clay Minerals Committee of the National Research Council, the University of Missouri, and the State Geological Survey of Kansas.

About 250 geologists, mineralogists, chemists, physicists, ceramists, engineers, agronomists, etc., representing many universities and laboratories from the United States and Canada were present. An object of the Conference was to bring together people from all fields interested in clays so that they might discuss problems of mutual interest which cross the boundaries of particular disciplines.

The Conference gave particular attention to the problem of techniques for identifying clay minerals in complex mixtures such as occur in many Recent sediments, and to the development of clay minerals in diagenetic and weathering processes.

The Conference was preceded by a one-day field trip to examine the Putnam soil profile and deposits of flint and diaspore clays.

The Great Lakes Research Institute, an organization sponsored by the University of Michigan, held a conference on problems of the upper Great Lakes on July 29–31, 1953, at the University Biological Station at Douglas Lake, Michigan. The principal purpose of the conference was a delineation of the present status and objectives of research on the upper Great Lakes in the fields of geology, hydrology, meteorology, limnology and fisheries. The geology section was attended by S. G. BERGQUIST, Michigan State College, East Lansing; J. C. RULISON, Michigan Geological Survey, Lansing; F. T. THWAITES, University of Wisconsin, Madison; H. J. PINCUS, Ohio State University, Columbus; J. T. WILSON and J. H. ZUMBERGE, University of Michigan, Ann Arbor; and J. L. HOUGH, University of Illinois, Urbana, Chairman.

The Fourth Conference on Coastal Engineering was held at Chicago on October 29–31, 1953, under the auspices of the Council on Wave Research. The first day's program was devoted mainly to geological and sedimentary topics relating to the Great Lakes. The invited list of speakers included J. L. HOUGH on "Geologic history of the Great Lakes," H. J. PINCUS on "The motion of sediments along the south shore of Lake Erie, W. C. KRUMBEIN on "Statistical problems of sampling Lake Michigan beaches," and R. O. FISHER on "Charactics of bottom sediments along the Illinois shore line of Lake Michigan." The papers will be issued as a Transactions volume early in 1954, and copies may be had through the Council on Wave Research, Berkeley, California.

A program on statistics in Geology will be presented at the Washington meeting of the American Statistical Society on Tuesday, December 29. A paper of considerable interest to sedimentary petrologists will be "Analysis of variance models in sedimentary petrology," by J. C. GRIFFITHS of Pennsylvania State College. R. A. GULBRANSON will speak on "Problems of sampling a geological formation." All interested geologists are invited to this session. W. G. SCHLECHT of the U. S. Geological Survey is Chairman of the Session, and can supply details of meeting place.

An Earth Sciences Panel of the Committee on Statistics in the Physical Sciences was established in 1952, under the auspices of the American Statistical Association. Purposes of the Panel are to foster statistical sessions in subject-matter societies, to act as an integrating agency on applications of statistics in the earth sciences, and to sponsor earth science statistical programs in the American Statistical Association. A list of present Panel members is given in the November issue of the Journal of Geology. W. C. KRUMBEIN, Northwestern University, is Panel Chairman.

The American Geological Institute is pleased to announce that it has secured for its executive directorate the service of Mr. C. B. HUNT, recently chief of the General Geology section of the U. S. Geological Survey with headquarters in Denver, Colorado. Mr. HUNT assumed his duties on September 1, 1953.

Dr. HOWARD R. GOULD, formerly with the U. S. Geological Survey, recently has joined the staff of the Department of Oceanography, University of Washington, Seattle, as Assistant Professor. He is engaged in teaching and research in the field of submarine geology.

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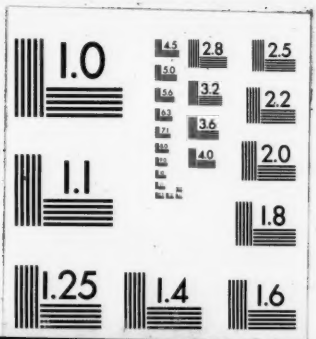
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